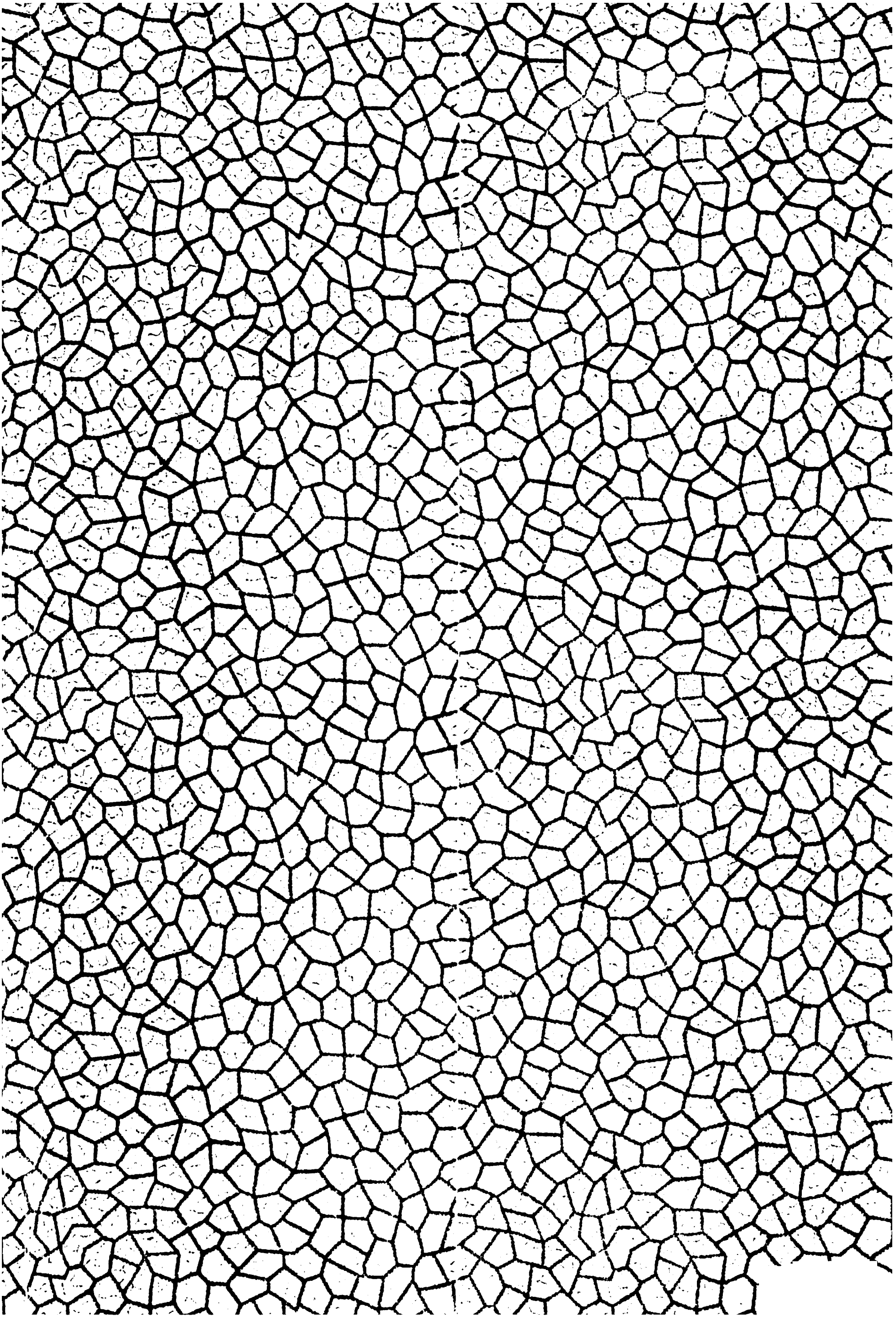

PRACTICAL WORK IN PHYSICS

PART III. LIGHT AND SOUND

WOOLLCOMBE

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Practical Work in Physics

FOR USE IN SCHOOLS AND COLLEGES

BY

Walter George

W. G. WOOLLCOMBE, M.A. (OXON.), B.Sc. (LOND.)

SENIOR SCIENCE MASTER IN KING EDWARD'S HIGH SCHOOL
BIRMINGHAM

PART III. LIGHT AND SOUND

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'Form, Light, and Sound is the physical triad on which are based all our aesthetic perceptions.'

PREFACE

AN essential feature in the four parts of *Practical Physics for Schools and Colleges*, of which this is the third, is to offer a fairly complete experimental course in the ground covered at but a trifling cost. The apparatus required is inexpensive, and may be readily obtained or easily made from the ordinary stock of a Chemical Laboratory. In addition to what is stated in the Introduction to the first part, it may be remarked that the subjects, here treated of, do not appeal so much to the student's power of observation as to that of his judgement. In most of the experiments in Light he has to decide what is to him the most definite image of an object, in Sound what the nearest approach to unison between two musical notes. In the latter case accuracy depends chiefly on his physiological perception of tone, which varies considerably in different persons. In the author's experience only five per cent. of the students he has had to deal with have so little 'ear for music' that the experiments in Sound for them are not possible.

KING EDWARD'S HIGH SCHOOL, BIRMINGHAM:
September, 1896.

CONTENTS

LIST OF EXPERIMENTS IN LIGHT.

Those experiments which are marked with an asterisk (*) are suitable only for older students.

A. Photometry.

B. Reflexion at Plane Surfaces.

C. Reflexion at Spherical Surfaces.

D. Refraction at Plane Surfaces.

E. Refraction through Lenses.

LIST OF EXPERIMENTS IN SOUND.

I. LIGHT

In addition to the apparatus and material, usually at hand in a Chemical Laboratory, the following will be required. Those in italics are not indispensable.

An optical bench and accessories (p. 20).

A spherometer (p. 24).

Wooden rod 20 cm. long, 1 cm. in diameter.

A Spectrometer and accessories (p. 13).

A glass prism.

Five Lenses:—*Plano-convex:* Plano-concave: Double concave: Two Double convex, one of short focal length (about 5 cm.).

A concave and a convex mirror. These may be watch-glasses silvered, as explained in *Practical Work in Heat*, Appendix B. 7.

A piece of well-polished plate glass $13 \times 9 \times 3$ c.c.

A water-tight trough about 15 cm. in length and 5 cm. in depth.

Five water-tight glass troughs 6 cm. square, two ·5 cm. wide, and one each of 1, 2, 3 *cm. in width.*

A thin piece of ground glass 5 cm. square.

Plane mirror.

A circle compass and a pair of dividers.

A packet of candles.

A packet of needles 4 cm. in length.

Cardboard

Two metre rules and one half-metre rule.

The apparatus required for this volume may be obtained from Mr. W. Groves, 89 *Bolsover Street, Portland Place, W., who will send a price list on demand.*

PRACTICAL WORK IN LIGHT

A. PHOTOMETRY.

THE *intensity of illumination* of a surface is defined as the quantity of light that falls normally on 1 sq. cm. of it.

1. To prove that the intensity of illumination of a given surface varies inversely as the square of its distance from the source of light.

Apparatus. A Candle or a Gas Flame as a source of Light: Cardboard: Scissors: Two pieces of stiff Wire 5 or 6 cm. long: Metre Rule.

Experiment. Cut out two screens of cardboard, one 2 cm. square, the other 20 cm. square. Divide up the larger screen into squares of 2 cm. in side by ink lines. Attach the screens by wax, one to each of the wires, and support them by clamps, or place them on the optical bench (p. 20). Place the small screen 20 cm. in front of the source, so that its centre is at the same height as the brightest part of the flame. If a gas flame is used, it ought, in this Experiment, to be placed edgewise to the screen, otherwise the edge of the shadow is too indistinct to be measured. Adjust the larger screen so that the shadow of the smaller one, cast by the flame, may fall centrally upon it. Since light acts, in general, as if it travels in straight lines, the

shadow is larger, the greater the distance between the two screens. All the light, which falls on the smaller screen, would, if the latter were removed, spread over and illuminate the area occupied by its shadow on the larger screen. Hence the quantities of light that would fall on unit area of the shadows, i. e. the intensities of illumination of the shadow-areas, when the larger screen is placed at different distances from the source, vary inversely as the shadow-areas.

After finally adjusting the heights of the screens so that the centre of the shadow may coincide with the centre of the screen on which it falls, place the latter 30 cm. off the source and measure the length, l, of the edge of the square shadow in terms of the divisions drawn on the screen. Now place this screen successively 40, 50, 60 cm. from the source, in each case measuring as above the lengths of the shadow-edges, and enter your results in a tabular form as follows:—

Distance of smaller screen from source = ... cm.		
Distance of larger screen from source (d)	Length of the shadow-edge (l)	$\frac{d}{l}$
...	...	...
...	...	...
...	...	...

We shall find that the ratios in the third column are constant, showing that the length of the edge of the shadow varies as its distance from the source. Its area therefore varies as the square of this distance, and, since the intensity of illumination varies inversely as the area, it varies also inversely as the square of the distance of the screen from the source.

Repeat the above, moving the smaller screen to a different distance from the source.

The *illuminating power* of a source of light is defined as the quantity of light which falls normally on 1 sq. cm. of a screen placed 1 cm. in front of the source.

If I_1, I_2, are the illuminating powers of two sources, the intensities of illumination of a screen placed d_1, d_2 centimetres from them respectively will be, according to Experiment 1,

$$\frac{I_1}{d_1^2}, \quad \frac{I_2}{d_2^2}.$$

If therefore we place the two sources at such distances d_1, d_2, from a screen so that it is equally illuminated by them, we have

$$\frac{I_1}{I_2} = \frac{d_1^2}{d_2^2},$$

or the illuminating powers of two sources are proportional to the squares of their distances from a screen equally illuminated by them.

2. To compare the illuminating powers of two given sources of light by Rumford's Shadow Photometer.

Apparatus. A cardboard, or preferably a ground glass screen, 20 cm. square: A screen of blackened cardboard or thin wood 90 × 20 sq. cm.: A wooden rod about 20 cm. long and 1 cm. in diameter: Two sources of light (e.g. a candle[1] and a gas flame): Two Metre Rules.

Experiment. Fix the square screen by wax to the table with its plane vertical, and about 10 cm. in front of its middle line fix the rod vertically. Place the metre rules, with their zero ends touching the lower edge of the screen, parallel to each other and perpendicular to the screen about 15 cm. apart, so that the rod is midway between them. Fix the longer screen with its shorter side in contact with the rod, and its longer side lying midway between the rules. By the right hand rule place one source of light about 20 cm. from the screen, so that it casts a shadow of the rod on the left hand side of the screen. By the side of the other rule place the other source, so as to cast

[1] If for one of the sources of light we use a standard candle (sperms, 6 to the lb., burning 120 grains per hour), we get the illuminating power of the other in standard candle power.

a shadow of the rod on the right hand side of the screen. The shadow cast by the one source will be illuminated by the other. Now adjust as carefully as you can the distances, d_1, d_2, of the two sources so that the shadows may be equally illuminated. To make this adjustment accurately requires considerable practice and is always a matter of some difficulty, as different sources emit differently coloured rays in different proportions. Thus a gas flame contains more blue than a candle flame, and so one shadow will have a bluish, the other a reddish tint.

We may get a more accurate result by placing in front of each of the sources first a red, then a blue glass, and taking the average of the pairs of distances obtained in the two cases.

Repeat the above three times more, in each case altering the distances of the sources from the screen, taking care, if using a gas flame, to keep it a constant size throughout the experiments. Enter your results in a tabular form as follows:—

d_1	d_2	$\frac{d_1^2}{d_2^2} = \frac{I_1}{I_2}$.
...	...	...
...	...	...
...	...	...
	Mean =	...

The constancy of the ratios in the third column will be a measure of the accuracy of your observations.

N. B. This Photometer may be made a permanent piece of apparatus by fixing the component parts to a base board 100×20 sq. cm.

3. To compare the illuminating powers of two given sources of light by Bunsen's Spot Photometer.

Apparatus. Cardboard screen, 6 cm. square, out of which a central hole 2 cm. in diameter has been cut with a cork borer: Two sources of light: Two pieces of silvered glass about 3 cm. square: Five similar candles: Metre Rule.

Experiment. Paste over the hole in the cardboard screen a piece of ordinary white note-paper. Rub in a little oil at the centre making a transparent circular spot about ·75 cm. in diameter. Since more light can get through this spot than the rest of the paper, the spot appears brighter or darker than the surrounding part, according as you look at the side turned away from or towards a source of light. Fix the screen on a support between the two sources of light, so that they are at the same height as the centre of the spot. The optical bench (p. 20) may be used. Move the screen to and fro until it is in such a position that the spot cannot be distinguished, in consequence of the whole surface of the paper being uniformly illuminated. In making this adjustment hold on each side of the screen a piece of silvered glass, at such angles as to allow both sides of the screen to be seen at the same time. It is rarely possible to cause the spot to disappear entirely owing to the presence of extraneous light, and the unequal absorption by the two parts of the disc. Measure the distances d_1, d_2, of the screen from the two sources.

Repeat the above three times more, in each case altering the distance between the sources and the screen, and enter your results in a tabular form as in Experiment 2.

If there is a third source of light, I_3, at hand, compare its illuminating power with each of the above two, and test the accuracy of your observations by finding whether the mean values of $\frac{I_1}{I_3}$ and $\frac{I_3}{I_2}$, when multiplied together, equals the mean value observed of $\frac{I_1}{I_2}$.

Again, place one of the candles on one side of the screen, and on the other side place four similar candles close together in a line parallel to the plane of the screen. Adjust until the spot cannot be distinguished, and measure distances, as before. Repeat this three times more, in each case altering the distances of the candles from the screen. We shall find the distance of the four candles to be twice the distance of the single one, showing that one candle at twice the distance of an

equal one produces one quarter of the intensity of illumination. Hence the intensity of illumination of a screen varies inversely as the square of its distance from the source, which we proved in Experiment 1 by a different method.

Compare the intensities of light given out by the same gas flame in different directions, by successively placing the flame so that its surface is perpendicular, and then parallel to the line joining it with the spot screen, in each case comparing the intensities with another source.

***4. To determine the coefficients of extinction and of absorption of a solution of copper sulphate of given strength.**

Apparatus. In addition to the apparatus of Experiment 3, we shall want five water-tight glass troughs 6 cm. square, two ·5 cm. wide, and one each of 1, 2, 3 cm. in width: Solution of copper sulphate.

Experiment. Fill the troughs with the solution of copper sulphate. Place one of the narrowest in front of the candle, the other in front of the gas flame. If I, i be the intensities of the light of the gas and candle flames passing through the solution respectively, and D, d the distances of the screen from each when the spot disappears,

$$\frac{I}{i} = \frac{D^2}{d^2}.$$

Replace the trough in front of the gas flame successively by the troughs of 1, 2, 3 cm. in width. If I_1, I_2, I_3, and D_1, D_2, D_3 be respectively the intensities of the light passing through, and the distances of the screen from the gas flame when the spot disappears, keeping the distance, d, between the candle and the screen constant,

$$I : I_1 : I_2 : I_3 : : D^2 : D_1^2 : D_2^2 : D_3^2.$$

If ϵ is that fraction of the incident light that passes through a thickness of 1 cm. of the solution

$$I_1 = \epsilon I \text{ or } \epsilon = \frac{D_1^2}{D^2},$$

$$I_2 = \epsilon I_1 = \epsilon^2 I \text{ or } \epsilon^2 = \frac{D_2^2}{D^2},$$

$$I_3 = \epsilon I_2 = \epsilon^2 I_1 = \epsilon^3 I \text{ or } \epsilon^3 = \frac{D_3^2}{D^2}.$$

Observe whether the values of ϵ, calculated from the above three results, coincide. The coefficient of absorption is that fraction of the incident light that is absorbed by a thickness of 1 cm., and is therefore $1 - \epsilon$.

Repeat the above, using water.

B. Reflexion at Plane Surfaces.

It can be shown that we can in general treat light as travelling in straight lines through a homogeneous medium such as air, water, glass—the straight lines being called *rays* of light. We cannot isolate a single ray, and we have therefore to deal with a collection of rays chosen in each case to suit the conditions of our experiment—the collection of rays being called a *pencil.* Different names are given to pencils according to the relative directions of the rays composing them. If the source of light is a long way off (e. g. in the case of the sun) the rays that reach us are approximately parallel to each other, and any collection of them is called a *parallel pencil* of rays. If the rays from a source of light separate further from each other as they travel from the source (e. g. rays from a lighted candle) they are said to form a *divergent pencil.* If, on the other hand, they approach each other (e. g. rays after passing through a burning glass) they are said to form a *convergent pencil.*

When a ray is incident on a surface separating two media of different densities, e. g. if a ray travelling through air strikes the surface of glass or water, it in general separates into three portions. One part, called the *reflected ray*, is turned back at the surface into the first medium: another part, called the

refracted ray, enters the second medium, but not in the same straight line as before. A third part is scattered or dispersed at the point of incidence. The percentages of the intensity of the original ray which suffer these three changes depend chiefly on the angle at which the ray meets the surface and on the degree of polish of the surface. It is only the scattered part by which we are enabled to see various objects. The greater the polish of the surface the less the amount of light which is scattered. It is difficult therefore to see the surface of a polished mirror.

5. To investigate the laws of Reflexion of Light.

Apparatus. Thin plane Mirror about 3×7 sq. cm.: Cardboard about 15×20 sq. cm.: Packet of Needles about 4 cm. long: Half-metre Rule.

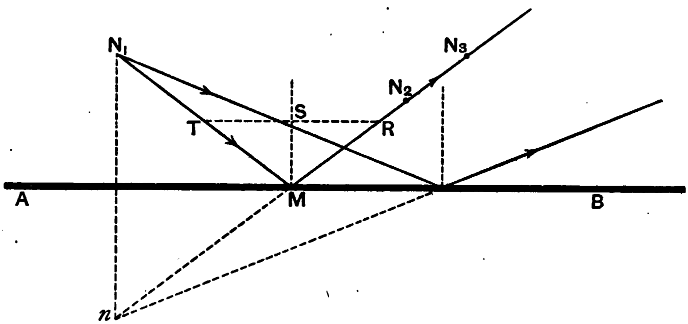


Fig. 1.

Experiment. Fix the cardboard to the table by drawing pins, and with a pencil line join the middle points of the longer sides. Attach the longer edge of the mirror by wax to the cardboard with its plane vertical, so that the edge of the silvered surface lies exactly along the line. Let AB (Fig. 1) be the trace of the mirror. About 5 or 6 cm. in front of it fix a needle, N_1, vertically. On looking into the mirror we see the image of the needle formed by rays that have been reflected at its surface. To fix the direction in which the reflected rays enter the eye place two needles, N_2, N_3, about 5 or 6 cm. apart, exactly in

a line with the eye and the image. Remove the mirror and the needles, and, joining N_2, N_3, by a straight line, continue it to cut AB at the point M. This is the direction of the reflected ray. Join N_1M, which must be the direction of the incident light from N_1. At the point M draw a normal to AB[2]. Join two points, R, T, equidistant from M, one point being on the reflected, the other on the incident ray, and let this line cut the normal at the point S. On measuring carefully the lengths RS, TS, we shall find them equal.

In the two triangles RMS, TMS, we have

$$RM = TM,\ MS \text{ common, and } RS = ST;$$
$$\therefore\ R\hat{M}S = T\hat{M}S \text{ (Eu. i. 8).}$$

Repeat the above twice more, in each case placing your eye in a different position.

We thus see that the angle, which the reflected ray makes with the normal to the reflecting surface at the point of incidence, is in all cases equal to the angle the incident ray makes with the normal, but on the other side of it. Since the length of the image is exactly the same as that of the needle itself, we also conclude that the reflected and incident rays are in the same plane as the normal to the surface at the point of incidence.

These two laws apply to reflexion at curved as well as at plane surfaces.

If we continue the directions of the reflected rays as drawn above, we shall find they all pass through the same point, n, (the image) behind the mirror, on the perpendicular produced from N_1 to the trace, and the same distance behind as N_1 is in front of the mirror. Fix a needle at the point n, and, on replacing the mirror and the needle N_1, we shall find that, however we move the eye, the image is always in the same straight line as the portion of the needle at n, visible above the edge of the mirror. The position of the image is therefore unique.

---

[2] Normals must be constructed geometrically by Eu. i. 11 (see *Practical Work in General Physics*, Appendix B. 4).

A *prism* is a portion of a substance included between two planes inclined at an angle to each other. The intersection of the two planes is called the *refracting edge*, and the angle between them the *refracting angle* of the prism.

6. To measure the angle of a prism of glass.

Apparatus. A glass prism: Cardboard: Packet of needles: a Protractor: Half-metre Rule.

Experiment. Draw on the cardboard two parallel straight lines about 1 cm. apart (Fig. 2), and fix vertically two needles, N_1, N_2, one on each line. Place the prism on the cardboard,

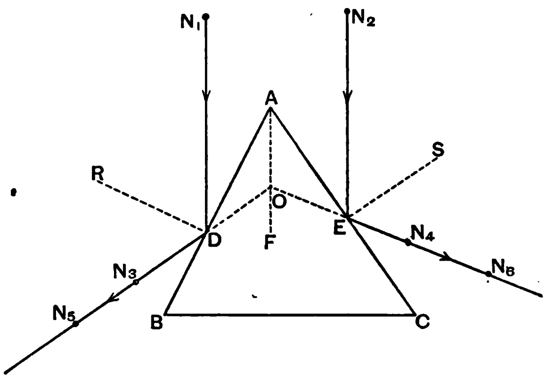


Fig. 2.

so that the angle A, which we require to measure, lies between the lines, and mark with a fine pencil the position of the edges of the prism. Looking into the face AB of the prism we see the image of N_1, formed by reflexion at this face. To fix the direction in which the reflected ray enters the eye, place two needles, N_3, N_5, exactly in a line with the eye, the point D, and the image of N_1. Looking into the face AC, place two needles, N_4, N_6, exactly in a line with the eye, the point E, and the image of N_2 seen by reflexion at this face. Remove the prism and the needles, and, joining $N_5 N_3$ by a straight line, continue it to meet at O the line joining $N_4 N_6$. The point O will be on the line through A parallel to the two lines through N_1 and N_2.

Now $N_5\hat{D}B = N_1\hat{D}A$ by the law of reflexion,

$N_5\hat{D}B = A\hat{D}O$ (Eu. i. 15)

$N_1\hat{D}A = D\hat{A}O$ (Eu. i. 29);

$\therefore \quad A\hat{D}O = D\hat{A}O,$

but $D\hat{O}F = A\hat{D}O + D\hat{A}O$ (Eu. i. 32);

$\therefore \quad D\hat{O}F = 2\,D\hat{A}O.$

Similarly $E\hat{O}F = 2\,E\hat{A}O;$

$\therefore \quad D\hat{O}E = 2\,D\hat{A}E.$

Half the angle, DOE, measured by the protractor, gives us the angle A of the prism.

Measure the remaining two angles of the prism in a similar way.

The Spectrometer. Carefully graduate a card circle of about 25 cm. diameter into degrees, making the circle of degrees to read inwards, and of 22·5 cm. in outer diameter. Mount it centrally on a board 27 cm. square. In the centre of a circular piece of wood, ·5 cm. in thickness and 6 cm. in diameter, bore a hole of such a size that it can turn freely, and without shake, round a steel screw (4 cm. long, No. 10), to be fixed in the centre of the graduated circle. Cut a strip, A, of thin wood, 28 cm. long, 3·75 cm. wide and ·3 cm. thick, in half. Glue the cut ends together with an overlap of 2·5 cm. Round one end and bore a hole, 1·5 cm. from this end, and mount on the screw. Cut another strip, B, 25 cm. long, round off one end, bore a similar hole, and mount on the screw.

[Size a piece of note paper with a weak solution of gelatine, and on it, when dry, construct an arc of a circle, 20·25 cm. in diameter, divided in degrees, and from it cut an arc of 10 degrees. Fix this with paper varnish to the lower surface of the glass strip with the scale next the glass, and place it so that the 10 divisions exactly correspond in length with 9 divisions of the divided circle. This serves as a circular vernier, by which the divisions of the circle may be read to tenths of a degree. If we dispense with the vernier, we can note the position of the

strip by reading the division at which its edge cuts the graduated circle.] Procure two convex spectacle lenses about 3 cm. in aperture and of about 20 cm. focal lengths. Make two cardboard tubes of the same diameter as the lenses. Let one of them, *P*, have a length equal to the focal length, and let the other, *Q*, be about 3·5 cm. longer. Blacken them inside. Fix against one end of the tube, *P*, one lens, and close the other end by a piece of cardboard, out of which a central hole has been cut having a diameter about three quarters that of the tube. Nearly close the hole by fixing over it two straight edges of cardboard parallel to each other and about 1 mm. apart, thus forming a narrow slit at the principal focus of the lens. This we shall call the 'collimator.'

Inside the tube, *Q*, 1 cm. from the end, fix a cork blank (i.e. a thin circular rim of cork). Rest the other lens upon the blank and fix it in position by pushing in another cork blank. This allows the lens to be replaced by another of different focal length, when necessary, as in Experiment 24. Fix a pair of very fine cross wires in *Q* at a distance from the lens equal to its focal length.

Procure a small convex lens about 1·5 cm. aperture and of 5 cm. focal length. Fix a blank in one end of a piece of brass tube 1·5 cm. in diameter and 4 cm. in length. Against it fix the small lens by wax. Cut a central hole in a cork in which the brass tube will slide smoothly, and fix the cork into the open end of *Q*. This constitutes the 'telescope.' Both *P* and *Q* may be neatly covered with black paper. Mount the collimator on the strip *A*, the telescope on *B*, adjusting them to such a height that their axes are in a plane parallel to the divided circle, and about 1·5 cm. above that of the central platform. Each part should be moveable by itself without causing either of the others to move [3].

7. To measure the angle of a prism of glass by the Spectrometer.

Apparatus. Spectrometer: Glass Prism: Source of Light.

Experiment. Fix the collimator arm by a small screw and

[3] Essentially the same description as that given in the Practical Physics course at the Royal College of Science, London.

then place the prism on the platform, so that the plane bisecting it passes through the slit, with its refracting edge a little nearer the collimator than the centre of the platform. Place the source of light behind the slit and look obliquely at either of the two faces containing the refracting angle. We shall see in each face an image of the slit formed by reflexion at it. Having by a slight adjustment of the prism succeeded in getting the two images to be formed simultaneously, fix the platform by a small screw. Focus the eyepiece on the cross wires. Move the telescope so that the intersection of the cross wires bisects the image of the slit reflected at one of the faces, and read the vernier or the division at which one edge of the telescope arm cuts the graduated circle. Keeping the platform fixed, move the telescope so that the intersection of the cross wires bisects the image formed by reflexion at the other face. Read position of the telescope. The difference between the two readings gives twice the angle of the prism (Fig. 2).

In a similar way find the remaining two angles of the prism.

C. Reflexion at Spherical Surfaces.

Spherical Mirrors. A spherical mirror is a portion of a thin spherical shell, one of whose surfaces has been rendered reflecting by being made of a polished material, e. g. speculum metal, or in the ordinary way by a coating of amalgam. A mirror is said to be *concave* or *convex* according as the centre of the sphere, of which it forms a part, is in front or behind the reflecting surface. The following definitions apply to both kinds, but, to fix our ideas, let us consider a concave mirror. Let RAS (Fig. 3) be a central vertical section of the mirror. C, the centre of the sphere, of which it forms a part, is called the *centre of the mirror*. The straight line through C, meeting the section at the middle point A, is the *principal axis*, and any other straight line through C meeting the mirror is called a *secondary axis*. The point A is called the *pole of the mirror*. If a luminous point is placed at a point P on the principal axis, any ray from it, e. g. PM, will, on striking the mirror, be

reflected from it in such a way that the reflected ray MQ makes the same angle with the normal, CM, to the surface at the point of incidence, M, as the incident ray makes with it on the other side (Experiment 5). The point Q, where the reflected ray cuts the principal axis, is called the *focus* of P. If we take into account, as we shall do, only those rays which strike the mirror on a small area around the pole A, we may consider that all of them after reflexion pass through the same point on the principal axis, and will there form a bright image of P. This point, which is the limiting position of Q when the point of incidence

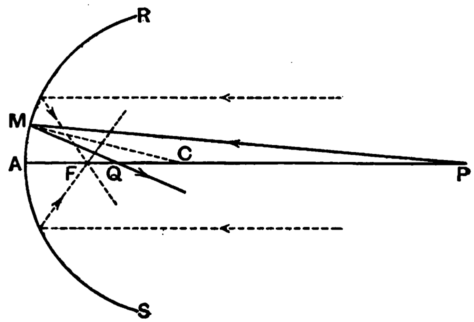


Fig. 3.

is close to A, is called the *geometrical focus* of P. If the luminous point were placed at Q, the same construction shows that its image would be formed at P, so that P and Q are interchangeable, and are therefore called *conjugate foci*.

The relation between the distances AP, AQ, of the object and its image from the pole, and AC the radius of the mirror, is proved in text-books to be

$$\frac{1}{AQ} + \frac{1}{AP} = \frac{2}{AC},$$

or, putting p, q, r respectively for AP, AQ, AC, we can write this equation, which we shall call the 'mirror equation,' as

$$\frac{1}{q} + \frac{1}{p} = \frac{2}{r}\text{[4]}. \qquad \text{(i)}$$

[4] All distances are to be measured in every case from the pole of the mirror or lens, and are to be considered positive if measured towards, negative if measured away from the source of light.

From this equation we can deduce the following relations between the positions of an object and its image, formed by reflexion at a concave mirror.

(*a*) If P is so far away that we may consider the rays of light from it to be parallel to the principal axis, we may put $p = \infty$ or $\frac{1}{p} = 0$, and we deduce that the distance of its image from the pole is

$$q = \frac{r}{2},$$

i. e. its image is at F, half-way between the pole A and the centre C. This point F is called the *principal focus*, and the distance AF the principal focal distance, or shortly the *focal length*, of the mirror. Calling this distance f, we may write Equation (i) as

$$\frac{1}{q} + \frac{1}{p} = \frac{1}{f}. \qquad \text{(ii)}$$

(*b*) Since for a givèn mirror the sum of the reciprocals of p and q is constant, p must increase while q decreases and vice versâ, i. e. P and Q move in opposite directions. Thus, as P moves up towards C, its image Q also moves towards C, until both coincide at the centre. For if $p = r$, $q = r$ also.

(*c*) As P continues to move past C up to F, Q moves away to the right, and, when P is at F, all rays from it, incident near the pole [*c*. p. 19], after reflexion are approximately parallel and Q is at an infinite distance.

The rays of light really pass through the images we have been considering till now, therefore the images are called *real*, and could be received on a screen placed at the different positions of Q.

(*d*) As P moves from F to A, on drawing a ray from P, in a given position between F and A, we should find that, after reflexion, it must be produced backwards to cut the principal axis. In this case the image is behind the mirror, and the rays do not really pass through it. Such an image is called a *virtual image*, and we cannot receive it on a screen. In this case AQ is measured from the pole away from the source of light, and therefore q is negative.

Writing the concave mirror equation thus

$$\frac{1}{q}=\frac{1}{f}-\frac{1}{p},$$

we see that q is negative, or the image is virtual and behind the mirror,

$$\text{if } \frac{1}{p} > \frac{1}{f}, \text{ i.e. if } p < f \text{ or if } P \text{ is between } A \text{ and } F,$$

and q is positive, or the image is real and in front of the mirror,

$$\text{if } \frac{1}{p} < \frac{1}{f}, \text{ i.e. if } p > f \text{ or if } P \text{ is to the right of } F,$$

which agrees with what was said above.

N.B.—The student should take a concave mirror, a candle flame and a screen pierced with a central hole, and, after adjusting their heights properly, should alter the distances of candle and screen from the mirror, and so realize experimentally the relations between them as explained above.

Precautions to be observed in experimental work. In all experiments connected with reflexion of light at, or refraction of light through, spherical surfaces, the accuracy of our measurements depends for the most part on our being able to obtain a well-defined and clearly cut image on a screen of a luminous object. To ensure this we have to take certain precautions and to make certain adjustments of the apparatus we use, so that the conditions under which we work may be favourable for this purpose. It is most important that these should be attended to very carefully, as otherwise much time will be wasted, and the student will fail to reap the benefit from the systematic procedure necessary to secure as accurate a result as his apparatus will allow.

To get a clearly cut image three chief things are necessary:

(*a*) The screen on which the image is to be formed must be as free as possible from extraneous light. If a dark room is not available, shade the screen by a piece of blackened cardboard[5] held in the hand.

[5] A good dead black varnish may be made as described in *Practical Work in Heat*, Appendix B. 6.

(*b*) The moveable pieces of apparatus in general use are: (i) the source of light, which may be a candle or preferably a gas flame; (ii) the object[6] to be illuminated—generally a wire stretched across a hole in a piece of cardboard; (iii) the reflecting or refracting surface; (iv) the screen on which the image is to be received. The heights of these must be adjusted so that the brightest part of the source of light, the centres of the object and screen, and the pole of the surface used are all in the same straight line.

(*c*) The image of each point of the object is at the point where the rays from it intersect after they have suffered reflexion or refraction. The image of the object is the locus or collection of these points of intersection of rays proceeding from the different points of the object. In the case of spherical surfaces only those rays from a given point which are incident near the pole intersect approximately in the same point after reflexion or refraction[7], so that to get a clearly cut image of an object we must employ some means of only using these rays for our experiments. In the case of spherical mirrors, it is best to cover them with a piece of blackened cardboard, out of which a circular hole has been cut to expose a small area of the mirror around the pole—the diameter of the hole being about $\frac{1}{8}$th of the aperture of the mirror.

In the case of lenses it is more convenient to cover the whole surface with lampblack by moving it about in the flame of a piece of burning camphor, floating in water, and then, by rubbing it off, expose a small area around the pole of the lens.

(*d*) The different colours composing white light are refracted differently on passing through a lens, and therefore the edge of the image so formed will be coloured with a reddish or bluish tint, according, in general, as the screen is nearer or further from the lens. This defect is called the 'chromatic aberration' of the lens (see Experiment 23). Unless the lens used is of

[6] Or the source of light itself may be used as the object.

[7] The fact that rays, striking the surface at a distance from the pole, do not intersect in the same point after reflexion or refraction at spherical surfaces is due to the defect of these surfaces, called 'spherical aberration.'

short focal length, this defect will be sufficiently neutralized by its covering of lampblack. If the edge of the image is still coloured, either allow the light to pass through a coloured glass, so as to use homogeneous light, or else choose the image intermediate between the red-edged and blue-edged images[8].

The Optical Bench. We may of course measure distances with a glass rod or with a metre rule, which has its zero end bevelled off to a point, but it is far more convenient to use an optical bench. This consists essentially of a slab of heavy wood, two metres in length, and 6 cm. square in section. Along one side are screwed two metre rules, end to end. Along the upper surface slide smaller slabs of wood, 5×6 sq. cm. in area, and about 2 cm. in thickness. Each has a brass lug screwed on to it, carrying a brass tube about 6 or 7 cm. in height, in which slides a brass rod carrying one of the pieces of apparatus in use. A screw through the tube serves to fix the rod at a convenient height. The small wooden slabs should have a curved piece of brass or a wooden cheek screwed on to either side to act as a guide when sliding along. The pieces of apparatus required to be fixed to the brass rods are:—

i. *Two lens* or *mirror holders*[9] (Fig. 4, i) consisting of a metal ring, at the lower part of which are two small grooved nuts *a*, *b*. On these the lens or mirror rests, and can be firmly fixed by an adjustable screw *S*, which also bears a pivoted grooved nut burred on to its lower end.

The lenses required will be a double convex, a double concave, a plano-convex, a plano-concave, and a short focus convex lens. Watch glasses, silvered with the solution described in *Practical Work in Heat*, Appendix B. 7, will serve as mirrors. Fill the watch glass with, or float it on, the silvering solution according as we require a convex or a concave mirror.

ii. *Two screen holders* (Fig. 4, ii), consisting of a metal frame with two clips to hold the screen. Three cardboard screens

[8] It is an advantage to observe the image in all cases through a magnifying glass or lens. A more accurate adjustment is thus possible.

[9] This lens holder and all other pieces of apparatus mentioned in this volume can be procured from J. J. Griffin and Son, Garrick Street, W.C.

5×4 sq. cm. will be required—two with holes of 1 cm. diameter bored centrally through them. Across the hole in one fix a piece of wire by wax; this we shall term the 'wire screen,' the other the 'perforated screen,' and the third the 'plane screen.'

iii. *A candle holder.* It is better to use a gas flame, in which case, instead of the brass supporting rod, use a brass tube, the top of which consists of an ordinary gas burner, having a by-pass to connect with the main supply.

In order to measure the distances between the pieces of apparatus, we may make a mark on the brass spring or

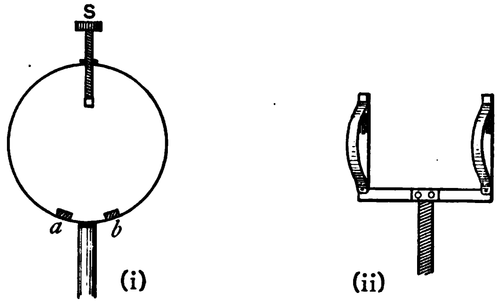


Fig. 4.

cheek in the same vertical plane as their centres, and read off the positions directly on the metre rules. Unless these marks are made with sufficient accuracy the following method is preferable. Support a piece of wire about 12 cm. in length horizontally and parallel to the bench, upon one of the sliding pieces of wood, and make a mark on the brass spring or cheek. Move the wire so that one end touches, say, the pole of the lens, and read the position of the mark on the graduated scale. Now move the wire till its other end touches, say, the screen, and read the position of the mark. The distance between the pole of the lens and the screen is the distance through which the mark has been moved added to the length of the wire.

i. *Concave Mirrors.*

8. To find the focal length of a concave mirror by parallel light.

Apparatus. Concave Mirror[10]: Perforated Screen: Half-metre Rule.

Experiment. Let light from a distant object fall upon the mirror—either light from the window itself, if it is three or four metres away, or from some prominent object out of doors. Place the screen in front of the mirror so that the light, on passing through the hole, may fall on the polar area of the mirror, and after reflexion may form a clearly cut image of the source on the screen. The plane of the screen should be parallel to the tangent plane at the pole, and the mirror should be slightly turned so as to throw the image a little on one side of the hole. Measure the distance of the screen from the pole of the mirror. Adjust the position of the screen four independent times[11].

We may consider the rays to fall on the mirror in a parallel pencil, and therefore they are reflected to the principal focus [(*a*) p. 17]. The mean of the four readings may be taken as the focal length, and twice this distance as the radius of the mirror.

9. To find the focal length of a concave mirror by coincidence of the object with its image.

Apparatus. Concave Mirror: Wire Screen: Source of Light[12]: Half-metre Rule.

[10] We shall always suppose, unless stated to the contrary, that the mirrors are covered with a perforated piece of cardboard, as explained at (*c*), p 19.

[11] In determining the position of the image formed by mirrors or lenses we should always take four readings, two on moving the screen towards, two on moving it away from the mirror or lens, and take the mean as the correct value.

If our readings have been made with equal care, the mean or average will be more nearly correct than either of the individual readings. The value of the result depends on the smallness of the differences of the individual readings. If one is very different from the others, this one should be cancelled and the measure repeated.

[12] If the source of light is a candle it is better in all cases to dispense with the wire screen and to use the candle flame itself as the object. Here

Experiment. Arrange the pole of the mirror, the middle of the wire, and the brightest part of the source at the same height. Place the eye behind the screen and we shall see the image of the screen hole reflected in the mirror. Arrange it to be concentric with the hole in the mirror cover. Keeping the eye fixed, move the mirror away from you. If the two holes remain concentric the adjustments are correct. Now place the source directly behind the screen so that as much light as possible may fall on the mirror. Move the latter towards the screen, turning it slightly so that a clearly cut image of the wire is formed on the screen after reflexion a little on one side of the hole [13]. Since the object and image are both at the same distance from the mirror they must be at its centre [(*b*) p. 17]. Measure this distance and adjust the screen three times more as usual. The mean of the four readings may be taken as the radius, and half its value as the focal length of the mirror.

N.B.—If a candle flame is used in this experiment as the object, hold a small cardboard screen close to the candle flame, with a piece bent at right angles, so that the bent piece may shade the part, on which the image is received, from the direct light from the candle.

10. To find the focal length of a concave mirror by the p and q method.

Apparatus. Concave Mirror: Perforated Screen: Source of Light: Plane Screen.

Experiment. Adjust the heights as usual, so that the light from the source which we use as the object, on passing through the screen hole, falls on the polar area of the mirror, and, after reflexion, forms an image a little on one side of the screen hole. Move the screen until the image is as clearly cut as possible,

and elsewhere the order in which the pieces of apparatus are written is the order in which they are to be arranged for the experiment.

When the optical bench is used, for convenience of calculation always place the pieces of apparatus that are to remain fixed during an experiment at decimetre divisions on the bench.

[13] If the image is distorted or blurred, the adjustments of heights are not correct and should be looked to again.

and measure its distance from the pole. Adjust the position of the screen three times more, as usual, and take the mean of the distances for the value of q, and measure the distance, p, of the object from the pole. Move the object further from the mirror and get another pair of values of p and q. Notice that in both cases the image is smaller than the object. Now remove the perforated screen, bring the object nearer the mirror, so that an image[14] is formed of it on the plane screen further from the mirror. In this case the screen will also be illuminated by the direct light of the source, and a little adjustment of the size of the flame, if a gas flame is used, will be necessary to get a satisfactory image. Measure the distance of the screen from the pole as before to get the value of q, and also the distance, p, of the object from the pole. Move the source to a slightly different position and get another pair of values for p and q. Notice that in both cases the image is larger than the object. On substituting the corresponding values of p and q in the mirror equation (ii) we can calculate f, the required focal length. Enter your results in a tabular form as follows :—

q	p	f
...	...	...
...	...	...
...	...	...
...	...	...
	Mean =	...

The Spherometer (Fig. 5) is an instrument consisting of an accurately turned screw, S, of $\frac{1}{2}$ m.m. pitch, working in a collar, supported by three pointed legs A, B, C, the lines joining the points forming an equilateral triangle, the point D of the screw itself forming the circum-centre of this triangle. The head of the screw consists of a brass plate, P, the circumference of which is divided into fifty equal divisions. Close to the circumference is a vertical edge, L, divided into millimetres

[14] So that a real image may be formed, the object must be further from the pole than the principal focus (p. 18).

and half-millimetres, numbered upwards and downwards from a zero in the middle of the edge. The divisions on the circumference bear two sets of numbers going round in opposite directions. The inner or outer set pass the edge in an increasing series according as the screw is raised or lowered. When the zero on the plate P is exactly opposite the zero on the edge L, the point D of the screw is in the same plane as the leg points A, B, C[15]. Starting with the zeros exactly opposite each other, if we turn the screw once round till the zero on the plate P again comes opposite the edge L, we shall have moved the screw vertically through $\frac{1}{2}$ m.m. and the zero on P will be found opposite the first division on the edge. If we raise the screw so that the first division on P comes opposite the edge, we shall have moved it vertically $\frac{1}{50}$th of $\frac{1}{2}$ m.m. or ·001 m.m. Suppose now we raise the screw until, say, the 37th division of the inner set of numbers on P cuts the edge L between the 3rd and 4th $\frac{1}{2}$ m.m. division.

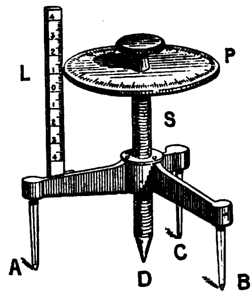


Fig. 5.

On the edge L, 3 small divisions = 1·5 mm.
On the plate P, 37 „ „ = ·37 mm.

∴ the distance the screw has been raised = 1·87 mm.
or ·187 cm.

In a similar manner we can find by how much we lower the screw, attending in this case to the outer set of numbers on P.

*11. To find the focal length of a concave mirror by the spherometer.

Apparatus. Spherometer: Concave Mirror: Half-metre Rule.

[15] This is so arranged by the maker, but it is advisable to see whether this adjustment is correct. Place the spectrometer on a piece of optically plane glass. Move the screw until, on gently tapping, the instrument does just not rock. The four points are then in the same plane and the zero on P ought to be exactly opposite that on L. If any 'zero error' is found, a suitable correction must be made to a reading taken with the instrument.

Experiment. Place the spherometer on the mirror so that the screw point is over the pole [16]. Lower the screw until, on gently tapping, the instrument does just not rock [17]. In this case the four points rest on the mirror. Read off the distance, h, through which the screw has been lowered.

Suppose Fig. 6, a, is a vertical section of the mirror, O its centre, A, D' being respectively the points of contact of one of the leg-points and the screw-point with the mirror. The distance, h, through which the screw has been lowered is DD'.

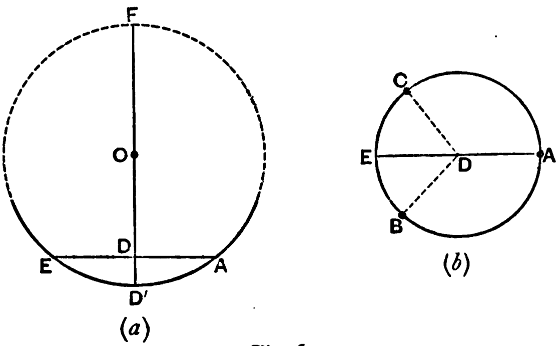


Fig. 6.

Now $$DD' \times DF = AD^2 \text{ (Eu. iii. 35)},$$
or, if r is the radius of the mirror,
$$h(2r-h) = AD^2.$$

To find AD, place the spherometer on a piece of paper, and bring the four points into the same plane. By gentle pressure make small indentations on the paper with the four points. Measure the distance AD (Fig. 6, b) from the indentation of the screw-point to that of the leg-point A and call it a.

Then $$h(2r-h) = a^2,$$
or $$r = \frac{a^2-h^2}{2h}.$$

[16] If the mirror is of uniform curvature all over its surface, we may of course place the instrument anywhere on it.

[17] To do this accurately requires considerable practice, but it is not difficult to find the position of the screw so that rocking may begin or cease on moving it up or down through a distance equal to one of the small divisions on P.

Halve the value of the radius of the mirror, so found, to get the focal length and compare your result with the values previously obtained.

ii. *Convex Mirrors.*

In the case of convex mirrors the radius is measured from the pole away from the source and therefore is negative, and the mirror equation becomes

$$\frac{1}{q}+\frac{1}{p}=-\frac{1}{f}. \tag{iii}$$

We see that q is always negative, i.e. the image formed by a convex mirror is behind it and virtual. Since therefore it cannot be received on a screen, we must find the focal length of a convex in a different way to that employed in the case of a concave mirror.

12. To find the focal length of a convex mirror by the aid of a convex lens.

Apparatus. Convex Mirror: Convex Lens: Wire Screen: Source of Light: Plane Screen.

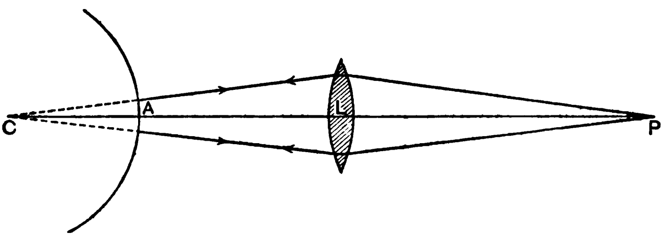


Fig. 7.

Experiment. Cover the lens with lamp-black and expose a small polar area [(*c*) p. 19]. Adjust the heights so that the pole of the mirror, pole of the lens, centre of wire, and the brightest part of the source are collinear. Place the source directly behind the wire screen, and place the lens at a greater distance from the screen than its focal length, so that it can form a real image of the wire [p. 39]. Move the mirror *A* (Fig. 7) until we see a clearly cut image of the wire *P* formed

on the screen by its side[18], and measure the distance between the mirror and the lens L. Adjust the mirror three times more, as usual, and take the mean of the measures as the distance AL. The light from the object, after refraction through the lens, has been reflected by the mirror back exactly along the same path to form an image coincident with the object. It is evident that the light must have been incident normally to the surface of the mirror, i. e. the rays if continued would intersect at the centre as in the figure. Now replace the mirror by the plane screen and move it from the lens till we get a clearly cut image of the wire formed by refraction through the lens. The screen is now in the position in which the centre of the mirror was before the latter was removed. Measure the distance between the lens and the plane screen. Adjust the latter three times more, as usual, and take the mean as the value of CL, the distance between the lens and the screen. The difference $CL - AL$ gives the radius of the mirror. Repeat the above three times more, in each case moving the lens to a different position, and take the mean of your results as the radius of the mirror, half of which is the required focal length.

*13. To find the focal length of a convex mirror by the p and q method.

Apparatus. Convex Mirror uncovered: Perforated Screen: Source of Light: Convex Lens of known focal length.

Experiment. Cover the mirror with a layer of lampblack. In a cork about 1 cm. in diameter bore a clean hole about ·75 cm. in diameter. Apply the cork to the pole of the mirror and with a gentle twist rub off a circular ring of the lampblack, the external diameter of which is RS (Fig. 8). Adjusting the heights as usual, we shall see on the screen a ring of light formed by the rays from the source P, which after passing through the hole have been reflected back on the screen from the exposed portion of the mirror.

To find AQ, or q, the distance of the image of P behind the

[18] See Note 13.

mirror, measure with a pair of dividers the external diameter, rs, of the white patch on the screen, and that, RS, of the exposed portion of the mirror, and note the distance AB between the screen and mirror.

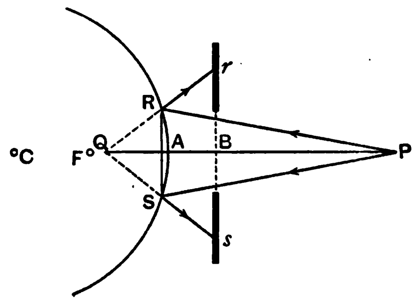


Fig. 8.

Since in the triangle Qrs, RS is parallel to rs, we have

$$\frac{AQ}{AQ+AB} = \frac{RS}{rs} \text{ (Eu. vi. 2)},$$

$$\text{i.e. } AQ \text{ or } q = \frac{AB \cdot RS}{rs-RS}.$$

Note the distance AP, or p, of the object from the mirror, and substitute for p and q in the mirror equation to get f, remembering to give the value of q the negative sign (Note 4, p. 16). Repeat the above three times more, in each case altering the distance of the source or the screen from the mirror, and enter your results in a tabular form, as follows:—

$RS = \ldots$ cm.				
rs	AB	q	p	f
...	...	...	...	...
...	...	...	...	...
...	...	...	...	..
...	...	...	...	...

Mean = ...

N.B.—As a particular case of this method, if the source sends parallel light to the mirror, $\frac{1}{p} = 0$ and the above expression for AQ gives us directly the focal length. To realise this condition, place between the source and the screen a convex lens, at a distance from the source equal to its known focal length. In this case parallel light emerges from the lens and on striking the mirror diverges from the principal focus of the latter. Measuring RS, rs, and AB, substitute their values in the above expression for AQ.

Again, if under these conditions, we place the screen at such a distance from the mirror that the diameter of the white patch is twice that of the ring, i. e. $rs = 2RS$, then the distance AB between the screen and mirror gives us directly the focal length of the latter.

The student should make two or three determinations by each of these two particular methods and, comparing his results with those already found, notice which method gives the most accurate results.

To test them, the focal length should finally be found by using the spherometer, as explained in Experiment 11.

D. Refraction at Plane Surfaces.

14. To investigate the laws of refraction of light, and to find the refractive index of glass.

Apparatus. A piece of good plate glass $13 \times 9 \times 3$ c.c. with well-polished surfaces: Packet of Needles about 4 cm. long: Cardboard 15×20 sq. cm.: Circle Compasses: Half-metre Rule.

Experiment. Fix the cardboard to the table by drawing pins, and with a pencil line join the middle points of the longer sides. Place the plate glass on the cardboard, so that its front longer edge is coincident with the line. Let AB (Fig. 9) be the trace of this edge. At a point, N_1, close to the hinder surface of the glass, fix a needle vertically. On looking into the front surface

of the glass we see the image of the needle formed by the light that has passed through the glass and been refracted from the glass into the air. To fix the direction in which the refracted ray enters the eye place two needles N_2, N_3, about 5 or 6 cm. apart exactly in a line with the eye and the image. Remove

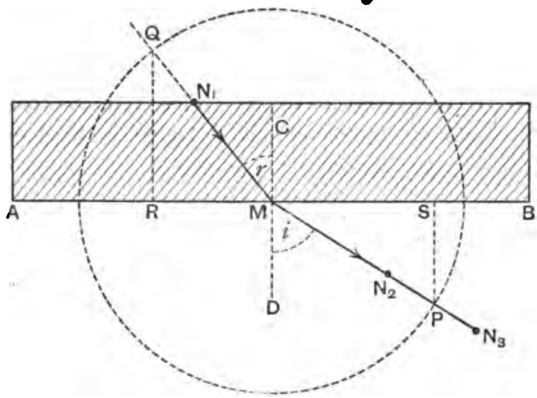


Fig. 9.

the glass and the needles and, joining $N_2 N_3$ by a straight line, continue it to cut AB at the point M. This is the direction of the refracted ray. Join $N_1 M$, which must be the direction in which the light travelled through the glass. With centre M and any radius describe a circle cutting MN_1 at Q and MN_2 at P. From Q and P drop perpendiculars QR, PS to the surface AB [19] and carefully measure the intercepts MS, MR.

Repeat the above twice more, in each case placing your eye at a different angle to the glass surface, and enter your results in a tabular form, as follows:—

MS	MR	$\frac{MS}{MR}$
...	...	...
...	...	...
...	...	...

[19] See Note 2.

If your measurements have been carefully made, you will find the ratios in the third column constant. The light would pass from the air to the glass in the reverse direction. Thus we conclude that when light passes from a rarer to a denser medium, it is bent towards the normal to the surface at the point of incidence, and that, whatever the angle of incidence may be, the ray will be refracted in such a direction as to make the ratio of the two intercepts, as above constructed, constant for the same medium. This ratio is called the *refractive index* of the medium and is known by the letter μ.

It is evidently equal to $\frac{\sin i}{\sin r}$, where i is the angle of incidence *PMD*, and r the angle of refraction *QMC*.

Since the length of the image is exactly the same as that of the needle itself, we conclude that the refracted and incident rays are in the same plane as the normal to the surface at the point of incidence.

These two laws apply to refraction at curved as well as at plane surfaces.

***15. To find the refractive index of glass by the spectrometer.**

Apparatus. Spectrometer: Glass Prism: Charcoal: Strong solution of Common Salt: Platinum Wire: Bunsen Burner.

Experiment. Fix the arm supporting the collimator of the spectrometer by a screw so that it cannot move. Focus the eyepiece of the telescope on to the cross wires. Arrange as near the slit of the collimator as can be done with safety a non-luminous Bunsen's flame. Since the different colours composing white light have different refractive indices, they are refracted differently by a prism. We must therefore select one colour for which the refractive index of the glass is to be found. Bind one end of the platinum wire round a piece of charcoal. Make the charcoal red-hot and dip it into the solution of salt and support the wire so that the charcoal is in the lower part of the Bunsen's flame. The light given out is monochromatic yellow. Since the slit is at the principal focus of the object glass of the

collimator, the light emerges from the latter in a parallel beam, and, since the telescope is focussed for parallel rays, we shall, on moving it to view the slit directly, see a clearly cut image of the latter coincident with the cross wires. Adjust them so that their intersection bisects the image of the slit, and read the vernier, or that division at which one edge of the telescope arm cuts the circular scale. Now fix the prism[20] on the moveable platform with a small bit of wax, so that its refracting edge is vertical and over the centre. Remembering that light on passing through a prism is bent towards the base, arrange the telescope and prism so that, on looking through the former, we see the image of the slit formed by refraction through the latter. The angle between the direct view of the slit and the direction in which the light emerges from the prism is called the *angle of deviation.*

On rotating the platform towards the line of direct view and following the image of the slit with the telescope, we shall notice that the image moves up to a certain point and then begins to move back again. At the turning-point the light that emerges from the prism makes the smallest angle with the line of direct view, i. e. suffers *minimum deviation.* To measure this angle, move the platform and telescope, keeping the image of the slit in the field of view, until the cross wires in the latter bisect the image of the slit exactly at the turning-point, and read the position of the telescope as before. The difference between the two readings you have taken is the angle of minimum deviation, D.

If A is the refracting angle of a prism, and D the minimum deviation that light suffers on passing through it, it is shown in the text-books that the refractive index of the medium, of which the prism is made, is given by

$$\mu = \frac{\sin \dfrac{A+D}{2}}{\sin \dfrac{A}{2}}.$$

[20] It is as well to cover the face of the prism opposite the refracting edge with a piece of paper, as otherwise the images formed by total internal reflexion may be confusing.

Knowing A, or finding it as in Experiment 7, substitute its value and that of D, just found, in the above expression, to get μ.

Repeat the above, using successively the other two angles of the prism as refracting angles and take the mean of the three values of μ as the required refractive index of the glass.

N. B.—The refractive index of a liquid may be determined as above by enclosing it in a glass bottle made in the shape of a prism. The sides of the bottle should be made of optically plane glass, for only in this case will the deviation of the light be unaffected by its passing through the glass sides. Determine thus the refractive indices of the liquids used in the following two experiments.

16. To find the refractive index of a liquid (Method 1).

Apparatus. Two Coins: Gas Jar: Half-metre Rule.

Experiment. Drop one coin into the jar and nearly fill it with water. Each ray of light that proceeds from the coin, on passing out of the water, is refracted away from the normal to the surface at the point of emergence. On placing the eye vertically over the jar the pencil of rays that enter the eye, being more divergent after emergence than before, will, if produced backwards, meet at a point in the water above the coin. At this point the eye will see the image of the coin. To fix its position, hold the other coin close to the outside of the jar and move it up and down until it appears to be at the same height as the image of the coin in the water. It requires considerable practice to get the proper height, but after a few preliminary attempts the student will be able to judge it with sufficient accuracy. When the proper height is obtained, measure the vertical distance of the coin in the hand from the surface of the water. Make six independent measures and take the average as the distance, q, of the image below the surface of the water. Now measure the depth, p, of the coin inside the jar below the surface.

It is proved in text-books that the ratio of the distance, p, of an object, viewed through a plate[21] of a denser medium,

[21] A *plate* is a portion of a refracting medium bounded by parallel plane surfaces.

to the distance, q, of its image from the surface, is equal to the refractive index of the medium,

$$\text{or} \quad \frac{p}{q} = \mu. \tag{iv}$$

Find as above the refractive indices of Turpentine, Alcohol, and Glycerine.

***17. To find the refractive index of a liquid (Method 2).**

Apparatus. A watertight Trough about 15 cm. in length and 5 cm. in depth: a metal or glass Scale which can be laid in the trough: Three strips of thin Wood or Metal about 1 cm. wide and 2, 3, 4 cm. long respectively: Cardboard: Half-metre Rule.

Experiment. Fix on to the scale by wax, about a quarter of its length from the zero end, the longest strip, arranging it vertically so that the shorter edge of the face further from the zero of the scale exactly coincides with a centimetre division. Put the scale in the trough, and fix it by wax if necessary, so that it may not move when water is poured in. Cut out of a piece of cardboard, 5 × 2 sq. cm., a hole with a cork borer about ·5 cm. in diameter and across it fix two cross wires. Attach it by wax to that end of the trough nearer the strip, so that the intersection of the cross wires is in the same vertical plane as the middle line of the scale. Place your eye behind the cross wires so that it is in a direct line with their intersection and the middle line of the scale, and read the division of the scale at which the edge of the strip appears. Repeat this four times and take the mean of your readings. Now carefully pour water into the trough without disturbing the scale, until the top edge of the strip is *just* under the surface. Place your eye in the same position as before and read off the scale division, whose image appears at the edge of the strip.

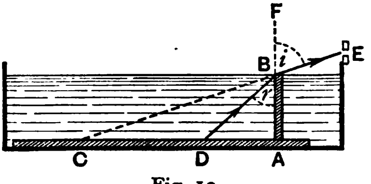


Fig. 10.

Suppose (Fig. 10) AB or h is the height of the strip, which

we must measure, AC or a, and AD or b, the distances respectively from A of the scale divisions read before and after the water was poured in.

The angle FBE or ABC is the angle of incidence, i, and ABD the angle of refraction, r.

$$\sin i = \frac{AC}{CB} = \frac{a}{\sqrt{h^2+a^2}},$$

$$\sin r = \frac{AD}{DB} = \frac{b}{\sqrt{h^2+b^2}},$$

$$\therefore \mu = \frac{\sin i}{\sin r} = \frac{a\sqrt{h^2+b^2}}{b\sqrt{h^2+a^2}}.$$

By substituting the observed values for h, a, b, we get μ, the refractive index of water.

Repeat the above, in each case taking a different strip and enter your results in a tabular form as follows:—

h	a	b	μ
...	...	...	...
...	...	...	...
...	...	...	...
		Mean =	...

Determine as above the refractive indices of Turpentine, Alcohol, and Glycerine, and compare your results with those obtained in the last experiment.

E. Refraction through Lenses.

Portions of media, e.g. glass, one or both of whose bounding surfaces are curved, are called *Lenses* and are of two chief kinds: (a) those that are thickest in the middle or *convex lenses*, (b) those that are thinnest in the middle or *concave lenses*.

Whatever may be the nature of the pencil of rays that falls on a lens, whether it be composed of parallel, convergent or divergent rays, it is, after passing through a lens, rendered either more convergent or more divergent than before, according as the lens is convex or concave. The former are therefore called convergent, the latter divergent lenses. The *principal axis* of a lens is the straight line joining the centres of the surfaces bounding the lens, the *pole* being the point where this line cuts the lens. Since we shall neglect the thickness of the lens the pole may be taken to be the point of intersection of the principal axis with either surface. When a pencil of rays parallel to the principal axis of a lens falls upon it, the rays (considering as before only those that are incident near the pole)

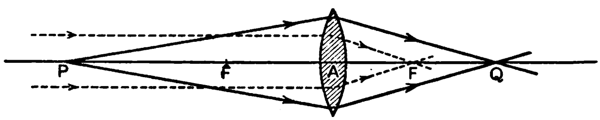


Fig. 11.

on being refracted through the lens converge to or diverge from the same point F according as the lens is convex or concave. The dotted lines in figures 11 and 12 show the action of a convex and a concave lens respectively on parallel light. The point F is called the *principal focus* of the lens, and is real in a convex, being on the other side, and virtual in a concave lens, being on the same side of the lens as the source. There is evidently a principal focus on both sides of a lens according to the direction in which the light falls upon it. The distance of this point from the pole of the lens is called its principal focal distance, or shortly its *focal length*.

If a luminous point P is placed on the principal axis of a convex lens (Fig. 11) further from it than its focal length, the rays, incident near the pole, will, after refraction, form a real image on the other side at the point Q, called the *geometrical focus* of P. If the luminous point were placed at Q, its image would be formed at P, so that the two points are interchangeable

and are therefore called *conjugate foci.* The relation between the distance AP, or p, of the object, the distance AQ, or q, of its image from the pole and, f, the focal length of the lens, is shown in the text-books to be

$$\frac{1}{q} - \frac{1}{p} = \frac{1}{f}, \qquad \text{(v)}$$

which we shall call the 'lens equation.'

In the case of a convex lens, in which AF is measured away from the object[22], f is negative and the equation becomes

$$\frac{1}{q} - \frac{1}{p} = -\frac{1}{f}. \qquad \text{(vi)}$$

From this Equation we can deduce the following relations between the positions of an object and its image formed by refraction through a convex lens.

(*a*) If P is so far away that we may consider the rays of light from it to be parallel to the principal axis, we may put $p = \infty$, or $\frac{1}{p} = 0$, and we deduce that the distance of its image from the pole is

$$q = -f,$$

i. e. the rays after refraction will converge to the principal focus F on the other side of the lens.

(*b*) Since for a given lens the difference of the reciprocals of p and q is constant, p and q must both increase or both decrease together, i. e. P and Q move in the same direction. Thus, as P moves up towards the lens, its image, Q, moves further away, until P reaches F, when Q is at an infinite distance, i. e. the rays from P after refraction are parallel to the principal axis. The rays of light really pass through the images we have been considering till now, therefore they are real and could be received on a screen placed at the different positions of Q. AQ is measured from the pole away from the source of light and therefore q is negative.

(*c*) As P continues to move nearer the lens, the refracted rays, though rendered less divergent than before, are not sufficiently

[22] See Note 4.

convergent as to cut the axis on the further side of the lens. Their directions if produced backwards will intersect at a point Q on the same side of the lens as, but behind, the point P. These rays do not really pass through Q, therefore the image is a virtual one and cannot be received on a screen. Since AQ is now measured from the pole towards the source, q is positive.

Writing the convex lens equation thus,

$$\frac{1}{q} = \frac{1}{p} - \frac{1}{f},$$

we see that q is negative, or the image is real and on the further side of the lens,

if $\frac{1}{p} < \frac{1}{f}$, i. e. if $p > f$ or if P is further from the lens than F,

and q is positive, or the image is virtual and on the same side of the lens as the object,

if $\frac{1}{p} > \frac{1}{f}$, i. e. if $p < f$ or if P is nearer the lens than F,

which agrees with what was said above.

N. B.—The student should take a convex lens, a candle flame and a screen, and, after adjusting their heights properly, should alter the distances of candle and screen from the lens and so realise experimentally the relations between them as explained above.

i. *Convex Lenses.*

18. To find the focal length of a convex lens by parallel light.

Apparatus. (*a*) Convex Lens[23]: Half-metre Rule: (*b*) Source of Light: Wire Screen: Convex lens: the Spectrometer telescope.

Experiments. (*a*) Place the zero end of the Half-metre Rule against a white wall opposite the window and hold the lens in a vertical position on the rule, so that light from a distant object falls upon it—either light from the window itself, if it is

[23] We shall always suppose, unless stated to the contrary, that the surface of the lens, excepting a small polar area, is covered with a layer of lamp-black, as explained at (*c*), p. 19.

three or four metres away, or from some prominent object out of doors. Move the lens along the rule, holding it parallel to the wall, until it forms a clearly cut image of the object on the latter. Read the distance between the lens and the wall. Adjust the lens three times more as usual[24]. We may consider the rays to fall on the lens in a parallel pencil, and therefore they are refracted to the principal focus [(*a*) p. 38]. The mean of the four readings may be taken as the focal length required.

(*b*) Focus the eye-piece of the telescope on the cross wires placed at the principal focus of the object-glass. Support the telescope horizontally and adjust the heights so that the source of light, the centre of the wire, the pole of the lens and centre of object-glass are collinear. Looking through telescope, move the wire screen till we see a clearly cut image of the wire coincident with the cross wires. Since the telescope is focussed for parallel light, the image we see of the wire must have been formed by rays that emerge from the lens parallel to each other and so enter the object-glass. The wire is therefore at the principal focus of the lens. Measure the distance between the two. Adjust the lens three times more, and take the mean of your results as the required focal length.

19. To find the focal length of a convex lens by the *p* and *q* method.

Apparatus. Source of Light: Wire Screen[25]: Convex Lens: Plane Screen.

Experiment. Arrange the heights so that the brightest part of the source, the centre of the wire, the pole of the lens and the middle of the plane screen are collinear. Place the eye behind the lens and, viewing the wire through it, move the lens away from you. If the wire remains in the centre of the field of view the adjustments are correct. Place the source directly behind the wire screen and move the lens until a clearly cut image[26] of the wire is formed on the plane screen[27]. Measure

[24] See Note 11. [25] See Note 12. [26] See Note 13.

[27] This will only obtain if the object is at a greater distance from the lens than its principal focus (p. 39).

its distance from the lens. It will be found that the image is larger or smaller than the object, according as it is further from or nearer to the lens than the object. Adjust the position of the screen three times more as usual[28] and take the mean of the measures as the value of q corresponding to the distance, p, of the object from the lens, which we also must measure. Find thus six pairs of values of p and q, in each case altering the distance of the object from the lens. By substituting their values in the lens equation (v) and remembering to give the negative sign to q[29], we shall get for each pair a value for f, which of course will be negative. Enter your results in a tabular form similar to the one given under Experiment 10.

Now reverse the faces of the lens and determine the focal length as before. Unless the lens is equi-convex we shall get a different value for f, since the focal length is not the same, unless the lens is very thin, when the order of the surfaces at which the refraction takes place is reversed.

*N. B.—The lens equation may be written

$$\frac{f}{q}-\frac{f}{p}=1,$$

which is the equation of a straight line, making intercepts, q, p, on the co-ordinate axes, and passing through the point whose ordinates are f, $-f$.

Each pair of values of q and p gives a different straight line passing through the same point. Plot on a piece of curve paper the values of p and q on the rectangular axes, and, joining the corresponding pairs, we find the straight lines pass through the same point. The co-ordinates of this point should be each equal to the focal length above found.

By looking at the figure so drawn, we can recognise if our observations and measurements have been accurate, and, if not, in which an error lies.

20. To find the focal length of a convex lens by the motion of the lens.

Apparatus. Source of Light: Wire Screen or a Scale of 2 cm.

[28] See Note 11. [29] See Note 4.

divided into millimetres etched on glass or celluloid: Convex Lens: Plane Screen: a piece of Ground Glass 5 cm. square: Metre Rule.

Experiment. Adjust the heights as usual and place the source directly behind the wire screen, and the latter at such a distance from the plane screen that, on moving the lens between them, two images are seen, one larger, one smaller than the wire. If the distance between the object and plane screen is a, and the distance through which the lens has been moved to form the two images is l, it is proved in the text-books that the focal length of the lens is given by

$$f = \frac{l^2 - a^2}{4l}.$$

Note the position of the lens in which it forms a clearly cut smaller image. Adjust the lens three times more, as usual, and take the mean as the correct position. Now move the lens towards the object and determine as before its position when it gives a clearly cut larger image. Note the distance, l, through which the lens has been moved, and also the distance, a, between the object and the screen and substitute their values in the above expression for f.

Repeat the above three times more, in each case altering the distance between the two screens, and enter your results in a tabular form as follows:—

l	a	f
...	...	...
...	...	...
...	...	...

Mean =

N. B.—It is evident that there is only one position of the lens which will form an image equal in size to the object. In this case the distances of image and object from the lens are equal. Putting $p = q$ in the lens equation, we find each is equal to $2f$, or the distance between the image and object when both are the

same size is four times the focal length of the lens. We may measure the length of the wire and move both lens and plane screen till we find the image of the same length as the object. Dividing the distance between object and image by 4 we get f. It is better to use for the object a scale of 2 cm. etched on glass or celluloid, illuminated by the source placed behind it, interposing between them a piece of ground glass to get the object uniformly illuminated. Move the lens and screen till the image of a centimetre of the scale is exactly 1 cm. in length and proceed as above.

***21. To prove that the sizes of an object and its image are proportional to their respective distances from the lens.**

Apparatus. Source of Light: Wire Screen or Scale used in last experiment: Convex Lens; Plane Screen: Pair of Dividers: Metre Rule.

Experiment. Adjust the heights as usual, placing the source directly behind the object. Arrange the lens and plane screen so that a clearly cut larger image of the object is formed on the latter and measure its distance, q, from the lens. With the pair of dividers measure the exact length, I, of the image, and measure the distance, p, of the object from the lens as well as the size, O, of the object itself.

Repeat the above six times in all, in each case moving the plane screen nearer the lens. Arrange so that you get three images larger and three smaller than the object, and enter your results in a tabular form as follows:—

Size of object (O) = ... cm.				
Size of image (I).	p	q	$\frac{p}{q}$	$\frac{O}{I}$
... ...	... ...	... ...	... ...	... ...

It will be found that the pairs of numbers in the same horizontal line in the last two columns are the same. Those corresponding to the larger images will probably be the less satisfactory, as in this case a little difference in the value of q does not sensibly alter the distinctness of the image.

***22. To find the radii of the surfaces of a lens and so to determine its refractive index.**

Apparatus. Source of Light: Wire Screen: Double Convex Lens.

Experiment. Place the source directly behind the screen and adjust the heights as usual. Arrange the lens so that the surface, whose radius we require, is the further from the source. On moving the lens we shall find one position of it, not far from the screen, in which an image of the wire appears on the screen. Turn the lens slightly, so that the image may be thrown a little on one side of the hole. The image can only have been formed by a part of the light having been reflected at one of the surfaces of the lens, viz. by that surface further from the source, as this is the only one of the two which has its concavity turned towards the source, and therefore the only one which can form a real image by reflexion. Since the image and object are coincident, the light must, after reflexion at this surface, have retraced its path, and therefore must have been incident normally on the further surface; i. e. the focus of the ray after refraction at the nearer must coincide with the centre of the further surface. If the known focal length of the lens is f, the radius of the further surface s, and a the distance between the lens and the screen when the object and its image coincide, it can be proved (Appendix A, 2) that

$$s = \frac{af}{f-a}.$$

Make four observations in all as usual and take the mean as the value of a. Knowing f, or determining it as in Experiment 19, we get the required value of s by substitution in the above expression.

Now turn the lens round and determine, as above, the value

of r, the radius of the other surface. We can also determine r, s, by the spherometer and compare our results.

In the case of a lens which has one or both of its surfaces concave, we must turn the concave surface whose radius we require towards the source. It will then act as a concave mirror, and its distance from the screen when the object and its image coincide gives us the radius required (Experiment 9).

The focal length, f, of any lens whose radii are r, s, and whose refractive index is μ, is shown in the text-books to be given by

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r} - \frac{1}{s}\right), \qquad \text{(vii)}$$

where r is the radius of the surface turned towards the source. Knowing f, r, s, we can by substitution find μ. We must before substitution give r, s, their proper signs. With the usual convention for a double convex r is negative, for a double concave s is negative. If either surface is plane, its radius is infinite or its reciprocal $= 0$.

23. To determine the chromatic aberration of a convex lens.

Apparatus. Source of Light: Wire Screen: Convex Lens without a lampblack covering: Plane Screen.

Experiment. Since the different colours composing white light are refracted differently by a lens, the blue rays being more refracted than the red, the image will have its edges of a different colour according as the screen is nearer or further from the lens [(*d*) p. 19]. Thus the focal length, f_b, for the blue, is shorter than the focal length, f_r, for the red rays. Determine each of them as in Experiment 19, holding successively a good blue or red glass in the path of the light.

The difference between the two $f_r - f_b$ [30] is called the *Chromatic Aberration* of the lens.

[30] This will only be an approximate value (i) because we do not determine the focal lengths for the extreme colours of the spectrum, (ii) because the coloured glasses used probably let through other colours beside the blue and the red, therefore the images are not quite monochromatic.

Repeat the above with another convex lens of different focal length and show that the chromatic aberration is the greater the shorter the focal length.

24. To find the thickness of a lens.

Apparatus. Source of Light: Piece of Ground Glass 5 cm. square: a Lens: the Spectrometer Telescope, in which the object-glass is replaced by another convex lens about 7 cm. focal length.

Experiment. If there are no scratches on the surfaces of the lens by which we may distinguish them, make a mark with a fine ink line on each surface at the pole, one horizontal, the other vertical. Place the source near the lens with the ground glass between the two, so that uniformly diffused light may illuminate the lens. Adjust the heights carefully so that the optical axis of the telescope may be collinear with the pole of the lens. Look through the telescope and move it until you see the image of the mark on the nearer surface. Focus a small dot close to the pole and note the position of the telescope. This focussing had better be repeated four times and the mean taken. Now move the telescope till you see the image of the mark on the further surface and note the position of the telescope, as before, when a similar dot is exactly in focus. The very small areas near the poles on which the marks have been made refract light, as if they were parallel. Hence we may treat the light as having been refracted through a plate of glass, and apply equation (iv). The distance through which the telescope has been moved is the distance, q, from the nearer surface to the image of the mark on the hinder surface. Taking the refractive index, μ, of glass to be $\frac{3}{2}$, by substitution in the equation, we get, p, the thickness of the lens.

Now measure the thickness by the callipers and compare your results.

ii. *Concave Lenses.*

In the case of concave lenses (Fig. 12) the focal length is measured from the pole towards the source and therefore

is positive, and the concave lens equation becomes

$$\frac{1}{q} - \frac{1}{p} = \frac{1}{f}. \qquad \text{(viii)}$$

We see that q is always positive, i.e. the image formed by a concave lens is on the same side of the lens as the object and virtual. Since therefore it cannot be received on a screen, we must find the focal length of a concave in a different way to that employed in the case of a convex lens.

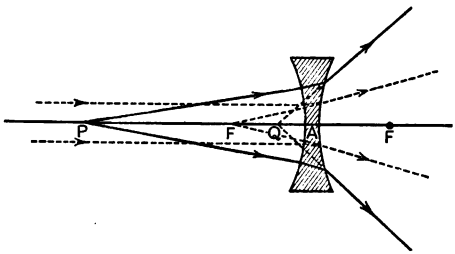


Fig. 12.

25. To find the focal length of a concave lens by combination with a convex lens of known focal length.

Apparatus. Source of Light: Wire Screen: Concave Lens: Convex Lens of sufficiently short focal length to form in combination with the concave lens a convergent system. Plane Screen.

Experiment. Place the two lenses together in one holder and find the focal length of the convex combination as in Experiment 19.

It is shown in the text-books that if F, f_1, f_2 are the focal lengths of a combination of two lenses and of the individual lenses respectively,

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2}.$$

In this case, if f_1 is the known focal length of the convex lens, and F the focal length of the combination above determined, we must give each the negative sign and substitute in the above expression to get f_2, the focal length of the concave lens.

26. To find the focal length of a concave lens by the p and q method, using a convex lens.

Apparatus. Source of Light: Wire Screen: Convex lens of sufficiently short focal length as will form with the Concave Lens a convergent system: Concave Lens: Plane Screen.

Experiment. Place the source directly behind the wire screen and adjust the heights as usual. Place the wire screen S (Fig. 13) further from the convex lens B than its focal length, and measure the distance of the plane screen Q from the convex lens when a clearly cut image of the wire is formed upon it. Adjust the screen three times more as usual and take the mean as the value of BQ. Now introduce the concave lens A between

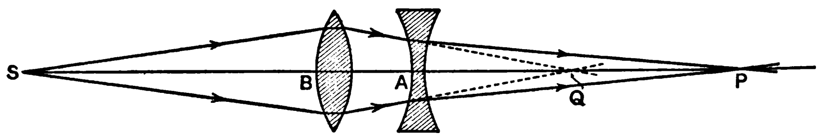


Fig. 13.

the two. Since light on passing through a concave lens is rendered more divergent, we shall have to move the plane screen further away, to P say, to obtain a clearly cut image of the wire formed by the light passing through the two lenses. Take the mean of four measures as usual for the value of AP, and measure the distance AB between the lenses.

Find the value of AQ, i.e. $BQ-BA$.

Since light can retrace its path, the image of an object placed at P after refraction through the concave lens would be formed at Q. Hence $AP=p$, $AQ=q$. Substituting these values in the lens equation we obtain f, the focal length of the concave lens, which of course will be found to be positive.

Repeat the above three times more, in each case altering the distance between the lenses, or the distance between the object and the convex lens, and enter your results in a tabular form as follows:—

BS	BA	BQ	AQ or q	AP or p	f
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
				Mean =	...

***27. To find the focal length of a concave lens by the p and q method, using a concave mirror of known radius.**

Apparatus. Concave Mirror of known radius: Concave Lens: Wire Screen: Source of Light.

Experiment. Place the source of light directly behind the screen, which must be at a greater distance from the mirror

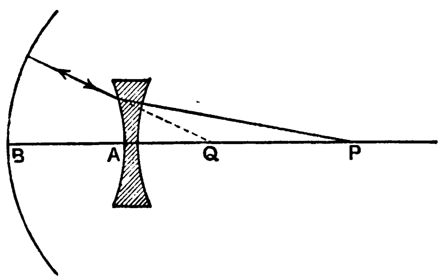


Fig. 14.

than its known radius. On moving the lens between the centre and pole of the mirror we shall find one position in which an image of the wire appears on the screen. Turn the mirror slightly, so that the image is thrown a little on one side of the hole. Since the image and object coincide, the light, on passing through the lens and being reflected at the mirror, must have retraced its path, and therefore must have been incident normally on the mirror; that is, the focus of the ray after refraction through the lens must coincide with the centre of the mirror. Adjust the screen four times, as usual, and take its mean distance from the lens as the value

of AP or p (Fig. 14). Measure the distance, AB, between the lens and mirror and subtract it from the known radius, BQ, of the latter and so get the value of AQ or q.

Substituting these values of p and q in Equation viii, we get the required focal length, f.

Repeat the above three times more, in each case altering the distance between the mirror and the lens, and enter your results in a tabular form as follows:—

Radius of concave mirror = ... cm.			
BA	AQ or q	AP or p	f
...	...	...	...
...	...	...	...
...	...	...	...
		Mean =	...

***28. To find the focal length of a concave lens by using a convex lens and a plane mirror.**

Apparatus. Plane Mirror: Concave Lens: Convex Lens: Wire Screen: Source of Light: Plane Screen.

Experiment. Place the source directly behind the wire screen, which must be at a greater distance from the convex lens than its focal length, and adjust the heights, as usual. Place the plane mirror close to the concave lens and move both together till a clearly cut image of the wire is formed upon the screen by its side. Note the position of the concave lens. Since the object and its image are coincident, the light, on passing through the lenses, must have been reflected by the plane mirror back along the same path. It must therefore have been incident normally on the mirror, i.e. must have emerged from the concave lens as a parallel beam. Hence the rays on passing through the convex lens must be converging to the principal focus of the concave lens on the further side. Remove the

latter and replace it by the plane screen and find its position so that a clearly cut image of the wire may be formed on it by refraction through the convex lens alone. Find the mean position of the screen after the four usual adjustments. The distance between the screen and the original position of the concave lens is the focal length of the latter.

F. SIMPLE OPTICAL INSTRUMENTS.

29. The Telescope and Microscope.

Apparatus. Two Convex Lenses, one of long, the other of short focal length: Plane Screen.

Experiment. (*a*) To illustrate the action of a telescope. Let light from a distant object fall on the lens of longer focal length (object-glass) and form an image upon the front of the plane screen. Focus the back of the screen with the other lens (eye-piece), placing your eye close to it, and adjust the heights of the lenses till their poles are at the same height. Remove the screen and look through the eye-piece. We notice an enlarged inverted image of the object. To get rid of spherical aberration, and so to get a more definite outline, place, in the position the screen occupied, a piece of cardboard, out of which a circular hole has been cut smaller than the size of the real image previously observed (diaphragm).

(*b*) To illustrate the action of a microscope. Place a small object in front of the lens of shorter focal length (object-glass) at a distance from it slightly greater than its focal length. Receive the image formed by it on a plane screen. Focus the back of the plane screen with the other lens (eye-piece), and adjust the heights of the poles of the lenses as above. Remove the screen and look through the eye-piece. We notice an enlarged inverted image of the object. Arrange diaphragm as before.

***30. To make a model of Hadley's Sextant.**

Apparatus. A piece of Wood 15 cm. square: Drawing Paper: two Plane Mirrors about 2·5 cm. square: a wooden Arm 11 cm. in length and ·75 cm. square in section: Circle Compass: Half-metre Rule.

Experiment. On a piece of drawing paper 15 cm. square draw two concentric arcs, one of 10 cm., the other of 11 cm. in radius, the centre being about 1 cm. from the middle point of an edge. Carefully graduate the space included between the arcs into 60 degrees, and join by the lines OA, OB, the centre to the $0°$ and $60°$ of the scale. Fix the paper on to the board. Into the centre O screw one end of the wooden arm and countersink the screw. The other end should be bevelled off and a mark made in the middle, by which the motion of the arm may be read off on the scale. Over the screw at O fix one of the mirrors, M, with its plane vertical and coincident with the middle of the arm's length, making it rigid by glueing a piece of wood at the back. Along OB, about 9·5 cm. from O, fix the other mirror, N, with its plane vertical and parallel to OA, making this also rigid in a similar way. A portion of its silvered surface should be rubbed off. Fix two nails close together near the edge of the board about 3·75 cm. off the top corner nearer OA.

In order to use this instrument to determine the angle subtended at the eye by two objects, P, Q, hold the board so that its plane passes through the two objects, and, placing the eye behind the nails, look at the lower object, P, directly through the unsilvered portion of the mirror, N. Move the arm till the image of Q, formed by reflexion of light from M to N and thence to the eye, overlaps P. It is proved in the text-books that the angle required is twice that through which the arm has moved.

APPENDIX A.

(1) *Refractive Indices for the D line.*

Flint Glass	1·63
Crown Glass	1·52
Alcohol	1·363
Benzine	1·5
Carbon Bisulphide	1·63
Ether	1·36
Olive Oil	1·47
Turpentine	1·48
Water	1·334
Glycerine	1·47

(2) *Prove that* $s = \dfrac{af}{f-a}$. (Expt. 22.)

Suppose the object at P (Fig 15). When it is at such a distance AP (p) from the lens, that its image is seen

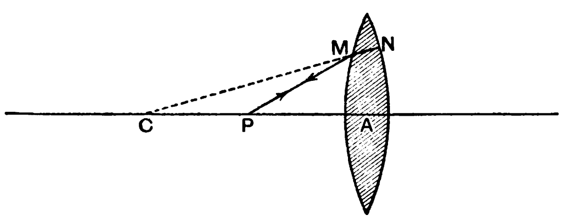


Fig. 15.

coincident with it, i.e. that the light is reflected from N back along the same path, the direction of the light MN through the lens must pass through the centre C of the hinder surface.

On refraction at the first surface of the lens, at *M*, if *r*, *s*, be the radii of the surfaces of the lens, at which the light enters and leaves the lens respectively, and if the distance of *P* from the lens is *a*,

$$\frac{\mu}{s}-\frac{1}{a}=-\frac{\mu-1}{r}.$$

Subtract from each side $\frac{1}{s}$ we get

$$\frac{1}{s}=\frac{1}{a}-(\mu-1)\left(\frac{1}{r}+\frac{1}{s}\right)=\frac{1}{a}-\frac{1}{f},$$

where f is the focal length of the lens,

$$\text{hence} \qquad s=\frac{af}{f-a}.$$

II. SOUND

IN addition to the apparatus and material usually at hand in a Chemical Laboratory, the following will be required:—

Monochord and accessories (p. 60).
Steel, brass and copper wires of No. 19, 21, 24 B. W. G.
Tuning-forks C_1 (128), C (256), E (320), G (384), C^1 (512).
Gong-hammer.
Two thin glass tubes, 40 cm. long, 2 cm. diam.
" " " 80 cm. " 2 cm. "
One glass tube each 45 cm. long, 2, 3, 4, 5 cm. in diam.
" " " 100 cm. " 1, 3, 4 cm. in diam.
" " " 60 cm. " 1 cm. diam.
A brass tube, a copper tube and a wooden rod, each about 1 metre in length and 1 cm. diam.
Piece of window glass 16 x 20 sq. cm.
Heavy block of wood 8 x 20 x 6 c.c.
Scale pan.
Box of gram-masses.
A metre and a half-metre rule.
Plane mirror.

PRACTICAL WORK IN SOUND

WHEN a tuning-fork is vibrating, the to and fro motion of each prong causes the layer of air, in contact with it, to be alternately compressed and rarefied. These compressions and rarefactions are transmitted through the air by its elasticity and, on reaching the ear, cause the tympanum to vibrate synchronously with them. The nerves in connexion with the tympanum carry the message to the brain and give us the impression of the sound given out by the tuning-fork. To realise how this happens, suppose the air to the right of a prong to be divided into parallel layers numbered 1, 2, 3, 4, ... When the prong moves to the right, layer No. 1 is compressed, and, being elastic, tries to regain its original density. When the prong moves back to the left, this layer not only expands to the left, but also tends to expand to the right, thereby compressing layer No. 2. No. 2, trying to regain its original density, expands to the left and tends to expand to the right, thereby compressing No. 3. When the prong moves forward again, No. 1 will be again compressed by it as well as by the simultaneous left-ward expansion of No. 2. Layer No. 3, being compressed, expands to the left and tends to expand to the right, thereby compressing No. 4. Since the prong is now again moving backwards and No. 1 is expanding, No. 2 is again

compressed by the simultaneous expansion of No. 1 to the right and No. 3 to the left. No. 2 now again expanding to the right and No. 4 to the left compress No 3 again. The left-ward expansion of No. 2 and the simultaneous forward motion of the prong compress No. 1, and the right-ward expansion of No. 4 compresses No. 5, and so on.

Thus by the vibration of each particle of air to and fro through a small distance on either side of its mean position of rest, a series of compressions and rarefactions are transmitted through the air and reach our ear. This constitutes the particular kind of *wave-motion* in free air to which sound is due. It is to be noticed that the vibrations of the air particles take place in the direction in which the sound is transmitted, and that the velocity of a given air particle is at any given instant equal in magnitude but opposite in direction to that of a particle at an equal distance the other side of the nearest compression or rarefaction.

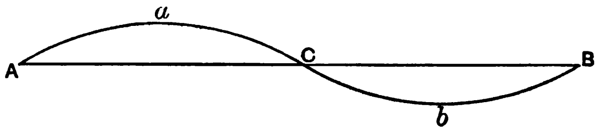
We may conveniently represent the motion of the air particles in one wave length in the following graphic way. Upon the straight line AB (Fig. 1, i) erect perpendiculars proportional to the displacement from their mean positions of rest of the vibrating particles at a given instant, drawing them above the line for those displaced to the right, below the line for those displaced to the left of their mean positions. The curve obtained by joining the extremities of these perpendiculars will give the simultaneous displacements of the particles at the given instant. At A and C, respectively the centres of a rarefaction and a compression, the particles are passing through their mean positions with the greatest velocity. At a and b the particles are in the positions of their greatest displacement and are momentarily at rest. The ordinates of the curve (Fig. 1, ii) represent the simultaneous velocities of these particles and the arrowheads the directions of their motion.

The distance through which a particle of air vibrates is called its *amplitude*, and is proportional to the velocity with which the particle passes its mean position. The *intensity* of the sound produced is proportional to the maximum kinetic energy of

the air disturbed, and therefore to the mass of air set in motion[1] and to the square of the amplitude of the vibrating particles.

The *wave-length* in air of the note given out by a tuning-fork is the distance between two successive compressions or rarefactions. The *phase* of motion of a given particle at any instant depends on the magnitude and on the direction of its motion, two particles being in the same phase, which are moving at any given instant in the same direction with equal velocities. The wave-length therefore is the distance between the

(i) DISPLACEMENT CURVE.



(ii) VELOCITY CURVE.

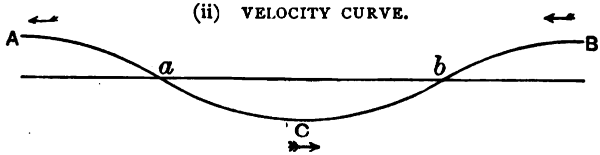


Fig. 1.

two nearest particles which are in the same phase. Now, while a prong of a tuning-fork has performed one complete vibration the adjacent layer of air has suffered one compression and one rarefaction, the rest of the layers synchronising with its motion. Since a complete vibration of each particle offers its quota to a compression and a rarefaction, the wave motion has passed through one wave-length during the time a particle of air performs a complete vibration. Hence we may define *a wave-length as the distance through which the sound has travelled during the time of one complete vibration of each particle of the medium through which the disturbance is travelling.*

The *pitch* of a note depends on the number of vibrations

[1] Hence the use of resonating boxes to intensify the sound produced by a tuning-fork or other musical instrument.

made by the sounding body in one second and, being measured by this number, is often called its *frequency*. The greater the number of vibrations per second, the higher is the pitch. If a sounding body makes n vibrations per second, each vibration causing a compression and a rarefaction, the sound will pass over n wave lengths in a second. Calling the wave-length λ, the distance the sound travels in one second, i.e. its velocity through the medium, will be given by

$$v = n\lambda. \qquad \text{(i)}$$

The lowest limit of frequency the average human ear can recognise as sound has been found by experiment to be that due to about 32 vibrations per second, the highest limit that due to about 38,000 vibrations per second.

The time of a complete vibration of a particle is called its *period*, and is equal to $\frac{1}{n}$-th of a second, where n is its frequency. If τ is the period, the above equation may be written

$$\lambda = v\tau. \qquad \text{(ii)}$$

If of two notes one makes twice as many vibrations in the same time as the other, the former is said to be the *octave* above the latter. The tuning-fork corresponding to the middle C of the piano, i. e. to the note on the ledger line between the bass and treble staves, has a frequency of 256 vibrations per second[2]. The note given out by the 8-foot organ pipe, or by the lowest string of the violoncello, is two octaves below and has a frequency of 64, that given out by the 1-foot pipe, being an octave above, has a frequency of 512 vibrations per second.

The **Monochord** or **Sonometer**, which we shall require for many of the experiments, consists of a wooden box, 112 cm. in length, 15 cm. wide and 10 cm. deep, made of well-seasoned pine, free from pitch, and straight grained. The top should be

[2] The standard concert pitch has in the course of time risen considerably. The middle *C* of the Philharmonic pitch at the present day has a frequency of 268. The tuning-forks in use in Physics are based on the old Handel pitch, in which the middle *C* has a frequency of 256.

·5 cm. thick and the sides 1 cm. thick. The ends of the box should be made of hard wood 2·5 cm. thick. Over the top glue a sheet of unglazed stiff paper which has been divided, perpendicularly to its longer sides, and numbered into centimetres and half centimetres. Near the ends of the box glue firmly triangular pieces of hard wood to serve as bridges across which the wires are to be stretched—the depth of the bridges being about 2 cm., and the distance between their upper edges exactly one metre. Into one of the hard ends insert two stout brass nails, each 2 cm. from the longer edges of the box, and a screw midway between them. Into the other end insert two piano screws, 2 cm. from the edges, and, midway, screw a small pulley so that a wire may rest on it, supporting an iron rod on which mass-blocks may be placed so as to hang freely. These blocks may be made of iron or lead, each about 2 kilograms, in which slots are cut, so that they may rest on a thick bolt at the lower end of the iron rod. To each of the brass nails attach firmly one end of a steel pianoforte wire [3], one of B.W.G. 19, the other 24. The other ends of the wires are to be secured to the piano-screws, and stretched by a piano key to the required pitch.

Two moveable bridges are also necessary, by which the length of the wires may be shortened at will. They are best made of narrow wedges of bone or wood, one edge being straight, to rest on the box, the other sharp, so that, by moving it under the wire, we can exert as little pressure as is necessary.

A violin bow, well resined, may be used to excite the wire, and care should be taken, by bowing the wire gently, not to alter its tension.

[3] The ends of wires may be heated, so as to soften them, before being attached to their supports.

A. Transverse Vibrations of Wires.

Suppose the middle point of a wire, fixed at both ends, is drawn aside from its position of equilibrium. Each molecule of the wire is under strain, and the nearer a molecule is to either of the ends the greater is this strain. If the wire is now let go, the energy of the motion of the molecules causes each to pass its position of equilibrium, to come to rest momentarily on the other side, and then to move back again. While the wire is vibrating it will chase the surrounding air into compressions and rarefactions, which convey to our ear the pitch of the note emitted. The amplitude of the middle point is the greatest, and as each molecule, in the course of its motion, pulls its neighbour after it, a pulse is transmitted along the wire by the enforced vibration of its particles to the right and to the left, the amplitudes of each particle decreasing towards either end. The pulse will have travelled twice the length of the wire while each particle has completed one vibration. Therefore, by our definition, the wave-length along the wire, vibrating transversely, is twice the length of the wire.

In a medium vibrating under constraint, e. g. a wire fixed at both ends, a rod clamped in the middle, air in an organ pipe, those parts which are approximately at rest but suffer greatest changes of tension or density are called *nodes*. Those parts which have the greatest motion and therefore suffer least changes of tension or density are called *internodes*, *loops* or *ventral segments*. In the wire fixed at its two ends and vibrating transversely, the middle point is the centre of a ventral segment, its two end are nodes[4].

[4] It is a general rule that whatever may be the medium we consider which is vibrating under constraint, and therefore forming nodes and ventral segments, the wave-length of the note transmitted in that medium is equal to twice the distance between two successive nodes, or between the centres of two successive ventral segments.

1. To prove that the pitch of a note emitted by a given wire under constant tension varies inversely as its length, i.e. $n \propto \frac{1}{l}$, the tension T being constant.

Apparatus. Monochord: two Tuning-forks of known frequencies.

Experiment. Key one of the monochord wires[5] to a somewhat lower note than that given by the fork of the lower pitch. Placing the moveable bridge under the wire, move it until a length is found which will give a note in unison[6] with one of the forks, whose frequency suppose is n_1. This length should be determined four times independently and the mean of the measures taken as the correct length, l_1— the effective length being the distance between the edges of the two bridges.

Now determine as above the length l_2, which will give a note in unison with the other fork of known frequency, n_2. It will be found that

$$n_1 : n_2 :: l_2 : l_1,$$

$$\text{or} \quad n_1 l_1 = n_2 l_2.$$

Again, place two moveable bridges under the wire and adjust their positions until two of the three divisions into which they divide the wire give notes in unison with the two tuning-forks.

[5] Tune the second monochord wire to the same pitch to be used as a standard. The pitch of the experimental wire should be repeatedly tested by comparison with the standard, and, if it has altered, should be readjusted.

[6] To ensure the unison of two notes we can use either of two methods: (α) *Method of Beats.* When two notes nearly in unison are sounded together, an alternate increase and decrease of the intensity of the sound is heard. This is caused by the resultant effect on the ear of the two systems of sound waves given out from the two sources. By placing the hand on the resonating box we can in general feel the 'beats' throbbing. The nearer two notes are to unison the less the number of beats. When quite in unison no beats are heard. Beats are more easily observed with low than with high notes and between two wires than between a wire and a tuning-fork. This method of tuning should always be adopted where possible, and with a little practice we can ensure perfect unison. (β) *Method of Resonance.* This depends on the well-known fact than when two notes given by different sources of sound are in complete unison, one, being caused to vibrate, will throw the other into vibration, and the note given out by the latter will be heard on *damping* (i.e. on stopping the vibrations of) the former.

Measure the lengths of these divisions and we shall find the same relation as before. In other words, in a given wire under constant tension, the pitch of the note emitted by it varies inversely as its length.

The *gamut* or *diatonic-scale* consists of a series of notes whose frequencies are proportional to the following numbers:—

$$24 : 27 : 30 : 32 : 36 : 40 : 45 : 48,$$

the first and last being at an interval of an octave. Dividing all through by 24, we get the ratios

$$1 : \tfrac{9}{8} : \tfrac{5}{4} : \tfrac{4}{3} : \tfrac{3}{2} : \tfrac{5}{3} : \tfrac{15}{8} : 2.$$

Since the frequency of a note given out by a wire varies inversely as its length, we can get the notes of the gamut, referred to the note, given by the wire vibrating as a whole, as the keynote, by measuring off successively lengths of the monochord wire, which are proportional to the following series of numbers:—

$$1 : \tfrac{8}{9} : \tfrac{4}{5} : \tfrac{3}{4} : \tfrac{2}{3} : \tfrac{3}{5} : \tfrac{8}{15} : \tfrac{1}{2}.$$

N.B.—The interval between two notes whose frequencies are as 3 : 2 is called a *fifth*.

2. To prove that, with a given wire, if the tension is altered, the lengths, which emit the same note, vary as the square roots of the corresponding tensions, i.e. for the same note $l \propto \sqrt{T}$.

Apparatus. Monochord: Mass-blocks: Steel, Copper, and Brass Wires of No. 21 B.W.G.

Experiment. Make a firm loop at one end of the steel wire, and hook it on to the screw of the monochord. Resting the wire on the pulley, attach the other end firmly to the rod on which the mass-blocks are to be placed. Carefully put as many blocks on the rod as the wire can bear. The steel wire of 21 B.W.G. will easily bear 20 kilograms. Key a monochord wire, so that it gives out a note somewhat higher than that given by the stretched wire. Placing the moveable bridge under the stretched wire, move it until a length is found to give a note in unison

with that given by the keyed wire. This length should be determined four times independently and the mean of the measures taken as the correct length, *l*. Observe the number of blocks stretching the wire, and to their mass add the mass of the supporting rod. This may be taken to represent the tension, *T*, of the stretched wire.

Take off each block successively and determine as above the corresponding lengths which give out the same note as the keyed wire, and enter your results in a tabular form as follows:—

... Wire: No. ... B. W. G.			
Tension in grams weight (T)	Length of wire giving same note (l)	l^2	$\frac{l^2}{T}$
...	...	...	...
...	...	...	...
...	...	...	...

Repeat this experiment, using another wire of different material and gauge.

The numbers in the fourth column ought to be constant[8], proving that the lengths of a given wire giving the same note vary as the square roots of the corresponding tensions.

3. To prove that, in wires of different material and gauge, under the same tension, the lengths emitting the same note vary inversely as the square roots of the masses of unit length of the respective wires, i. e. for the same note $l \propto \frac{1}{\sqrt{\mu}}$, where μ is the mass of 1 cm. of the wire.

Apparatus. Monochord: Mass-Blocks: Steel, Copper, and Brass Wires of Nos. 19, 21, 24 B.W.G.

[8] If the numbers are found to increase, the tension of the keyed wire has probably altered, hence the advantage of having a second wire as a standard to refer to (Note 5, p. 63).

Experiment. Attach the steel wire to the screw of the monochord as in the last experiment, and place as many blocks on the iron rod as will cause it to give out a medium note (about C). Key a monochord wire to a somewhat higher pitch. Placing the moveable bridge under the stretched wire, find as before a length, l, which will give a note in unison with the keyed wire. Substitute the other wires, successively stretching them with the same weight, and find the length of each giving a note in unison with the same keyed wire. Now cut off a piece from each wire, measure its length and find its mass. Hence determine the mass, μ, of 1 cm. of each wire, and enter your results in a tabular form as follows:—

Tension = ... gr. wt.				
Material of wire.	Gauge B. W. G.	Length giving same note (l)	Mass of 1 cm. (μ)	μl^2
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...

The numbers in the fifth column ought to be constant, proving that the lengths of different wires under the same tension, which give the same note, vary inversely as the square roots of the masses of unit length.

***4. To determine the pitch of the note emitted by a wire vibrating transversely.**

Apparatus. Monochord: Mass-Blocks: a Tuning-fork of known frequency: Brass Wire of No. 21 B.W.G.

Experiment. It can be shown on dynamical principles that the velocity with which transverse vibrations travel along a flexible wire fixed at both ends is given by the formula

$$v = \sqrt{\frac{T}{\mu}}, \qquad \text{(iii)}$$

where T is the tension or stretching force in dynes, and μ the mass of 1 cm. of the wire. Now the period of a complete vibration of the wire is the time required for the pulse to travel over twice its length (p. 62). Therefore, if n is the frequency of the note given out by the wire vibrating as a whole, and if l is its length,

$$v = 2\,ln. \tag{iv}$$

From (iii) and (iv) we get

$$n = \frac{1}{2\,l}\sqrt{\frac{T}{\mu}}. \tag{v}$$

The previous three experiments will have proved this relation experimentally.

Again, if r is the radius of the wire and d its density, $\mu = \pi r^2 d$, and this equation may be written

$$n = \frac{1}{2\,l\,r}\sqrt{\frac{T}{\pi d}}, \tag{vi}$$

showing that the pitch varies

$$\left.\begin{array}{l}\text{(}a\text{) Directly as the square root of the tension}\\ \text{(}b\text{) Inversely as the radius or the diameter}\\ \text{(}c\text{) Inversely as the length}\\ \text{(}d\text{) Inversely as the square root of the density}\end{array}\right\}\text{ of the wire.}$$

Attach the steel wire to the screw of the monochord as in the last experiment, and place as many blocks on the iron rod as will cause it to give out a note somewhat lower in pitch than that given by the tuning-fork. Placing the moveable bridge under the wire, find as before a length, l, which gives out a note in unison with the fork. Mark, measure, and cut off this length and weigh it. Hence determine the mass, μ, of 1 cm. Note the value of the total tension in grams weight and reduce it to dynes by multiplying by g, the acceleration of gravity. Substituting in equation (v) for T, l, and μ, we ought to get for n the same value as the known frequency of the tuning-fork.

Repeat this experiment with a wire of a different material and gauge, under a different tension.

5. To determine the pitch of a tuning-fork by the monochord and a fork of known frequency.

Apparatus. Monochord: two Tuning-forks, one, X, of unknown frequency, n; the other, F, of known frequency, N.

Experiment. Key the monochord wire to give a note of somewhat less pitch than that given by the fork which has the less frequency. Determine successively as before the lengths, L, l, of the wire which give notes in unison with the forks F, X respectively. Since the frequencies vary inversely as the lengths of the wire under constant tension,

$$n : N :: L : l,$$

or $$n = \frac{L}{l} N.$$

6. To compare the frequencies of two given tuning-forks graphically.

Apparatus. Two Tuning-forks of different frequencies used in the last experiment: Block of heavy Wood about $8 \times 20 \times 6$ c.c.: Piece of Glass about 16×20 sq. cm.: Half-metre Rule: Monochord.

Experiment. Screw the shanks of the two forks tightly into the 8×6 face of the block of wood, near and parallel to each other, so that the four prongs are at the same distance (not greater than 1 cm.) off the table, when the block is laid down. To the inner prong of each fork attach, by equal quantities of wax, a brush bristle, inclined at about 45° to them, so that the free ends may just touch the glass sheet, when placed underneath. Cover the glass with a thin layer of lampblack, by moving it about in the flame of burning camphor floating on water. Place the smoked glass on the table under the forks with its shorter edge touching the block, and adjust the bristles accurately. Put the forks into vibration by the bow or gong-hammer and quickly slide the glass from under them. It is as well to fix a straight-edge to the block to act as a guide to the glass in its motion. The bristle points will rub off the lamp-black and expose the glass along two sinusoidal lines of similar

shape to those in Fig. 2 [9]. At such corresponding points as *a*, *b*, . . . the forks were in the same phase, i.e. the prongs were moving in the same direction. From crest to crest on either line represents one complete vibration of the fork. If we count the number of complete vibrations on each line between pairs of points at which the forks were moving in the same direction, we obtain the number of vibrations made by each fork in the same time, and the ratio of these numbers is that of their frequencies.

Near each longer edge of the glass attach by wax a strip of cardboard so that we may rest a rule upon them without rubbing off the lampblack. Holding the rule parallel to the shorter edge of the glass, mark with a needle-point as many crests on the two wave-lines as are in the same phase. Count the number of complete vibrations between successive marks on each of the lines and take the average of these numbers for each fork to represent the ratio of their frequencies.

At least four such pairs of lines should be so treated and the average of the resulting ratios taken as the final result.

Now compare the frequencies of the forks by the monochord, as in the previous experiment, and compare your results.

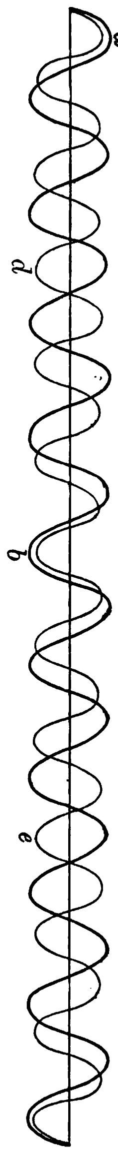


Fig. 2.

7. To show the existence of harmonics in a vibrating wire.

Apparatus. Monochord: narrow Strips of Paper (riders), not more than ·75 cm. long, bent slightly so as to be able to rest on the wire.

[9] The two lines are superposed in the figure for convenience. The figure represents the wave lines of two forks whose frequencies are as 5 : 6.

Experiment. We have so far only considered the note given out by a wire vibrating as a whole, which is called its *fundamental note.* We can show that, while vibrating as a whole, it is also divided into 2, 3, 4, . . . equal parts, each of which is vibrating simultaneously and independently of the others.

(*a*) Place three riders on the wire, dividing its length into four equal parts. Bow gently one-third of its length from one end. The two end riders fall off, the middle one remains; showing that the middle point is a node. The wire is therefore divided into two equal vibrating segments. Since the half wave-length of the corresponding note equals half the length of the wire[10], its frequency is twice that of the fundamental. The octave of the fundamental is therefore given out.

(*b*) Place five riders on the wire, dividing its length into six equal parts. Bow gently near the middle point. Nos. 1, 3, 5 riders fall, Nos. 2, 4 remain, showing that the wire is divided into three equal vibrating segments. The half wave-length of the note corresponding to this division, being one-third of the length of the wire, its frequency is three times that of the fundamental. The fifth of its octave is therefore given out (N.B. p. 64).

(*c*) Again, placing seven riders at equal distances, and gently bowing one-third of the length of the wire from one end, No. 2, 4, 6 riders remain. Since the vibrating segments are one quarter of the whole length, the note given out is the double octave above the fundamental.

With care we might show the existence of still higher notes. These notes are called the *overtones*, *upper partials*, or *harmonics*, and it is due to the mixture of them with the fundamental that we are able to distinguish different instruments giving out notes of the same pitch. The property of a note as depending on the number of harmonics present is called its *quality* or *sound-tint* (*Klangfarbe*). Stringed instruments and reed pipes are rich in harmonics, tuning-forks and organ pipes (diapason) produce but few.

[10] See Note 4, p. 62.

In order to recognise the harmonics individually in the wire, after bowing in each case as above, damp the point at which a node is formed by touching it momentarily with a feather. This causes all notes, except the one which has this point as a node, to vanish and we can recognise the harmonic at once.

N. B.—Equation (v) on p. 67 gives the number of vibrations of the fundamental note of the wire only. That it may include those due to the harmonics we must write it in the complete form

$$n = \frac{x}{2l}\sqrt{\frac{T}{\mu}}, \qquad \text{(vii)}$$

where x equals 1, 2, 3 . . .

***8. To prove the laws of the transverse vibrations of strings by Melde's method.**

Apparatus. A Tuning-fork of frequency 128: Cotton or Thread: Scale Pan: Box of Masses: Metre Rule: Gong-hammer.

Experiment. To the top of one of the prongs of the fork solder a small piece of brass about $\cdot 75 \times \cdot 25$ sq. cm. through which a small hole has been bored, and screw the shank of the fork firmly into the table. Passing one end of a piece of thread about 4·5 metres long through the hole, tie it firmly to the brass piece, and to the other end attach the scale pan. Pass the thread over a moveable support, e. g. a smooth nail or a pulley, about 4 metres off the fork, so that it is horizontal, the scale pan hanging freely. Place a mass of 100 grs. in the pan and arrange the fork so that its prongs vibrate in the direction of the length of the thread. On striking the fork sharply with the gong-hammer, adjust the distance of the support until we see the thread split up into a number of vibrating spindles or loops. The pitch of the fork is too high to allow the thread to vibrate as a whole, therefore, in order to adjust itself to the enforced vibration of the fork, it must split up into segments. Thus if there are four loops, it is vibrating four times as fast as it can vibrate as a whole. For a given length the frequency of vibration, as a whole, varies inversely as the number of loops.

(*a*) Move the support nearer the fork until the thread is sufficiently short to vibrate as a whole, and adjust the support until it is at the node. This adjustment is correct when the vibration of the thread lasts the longest. Measure the length between the fork and the support. Now move the support further from the fork until we get the thread to vibrate successively in 2, 3, 4 loops[11]. Measure each time the length of the thread between the support and the fork. We shall find the lengths vary as the number of loops. Therefore the frequencies of the thread vibrating as a whole, or the fundamental frequencies, vary inversely as the lengths,

$$\text{i.e. } n \propto \frac{1}{l}$$

when the tension is constant.

(*b*) Keeping the support at such a distance that four loops are formed when a mass of 100 grs. is placed in the scale pan, place masses in the pan so that the tensions, including the weight of the scale pan, are successively 400, 100, 25, 6·25 gram weights, and count the loops formed in each case. We shall find their number to be 2, 4, 6, 8 respectively[12].

Since the fundamental frequency varies inversely as the number of loops, which we see varies inversely as the square root of the tension,

$$n \propto \sqrt{T}$$

when the length is constant.

(*c*) Tie four strands of thread to the brass piece and twist them round to make a thread four times the mass of a single strand. Adjust it as before, placing the support at such a distance from the fork as would cause two loops in a single thread. On vibrating the fork we now observe four loops. Making an equal length of nine strands we should get six loops.

Since the fundamental frequency varies inversely as the number of loops, which we see varies as the square root of

[11] As the length is increased the fundamental frequency is lowered, hence, to adjust itself to the pitch of the fork, more loops must be formed.

[12] Since an increase in tension of a string of constant length raises the frequency, the number of loops becomes less as the tension increases.

the mass of the thread,

$$n \propto \frac{1}{\sqrt{m}}$$

when the length and tension are constant.

N. B.—In this position of the fork the string can only move above or below the horizontal line, when the prong is in its forward position, hence the period of its vibration is half that of the fork. If we now turn the fork through a right angle so that it vibrates perpendicularly to the direction of the length of the thread, the number of loops will in each of the above cases be doubled, as now the thread can synchronise with the fork and follow its vibrations.

B. Velocity of Sound through Gases.

The velocity, v, with which sound travels through solids, liquids, or gases, by longitudinal vibrations of the particles of the medium can be found on dynamical principles to be given by

$$v = \sqrt{\frac{E}{D}}, \qquad \text{(viii)}$$

where E is the coefficient of elasticity of the medium, and D its density.

(a) In the case of solids this coefficient of elasticity is the ratio of the stretching force in dynes per unit area of section of a solid rod or wire to the extension per unit length which this produces. Thus, if we apply a force of T dynes to a rod of length L cm., and sectional area a sq. cm., and if its length is thereby increased by l cm., its coefficient of elasticity is by definition

$$\frac{T}{a} \div \frac{l}{L} \quad \text{or} \quad \frac{TL}{al}.$$

This coefficient is called Young's Modulus, and is indicated by

the letter M. It is evidently that force per unit area which would double the length of the rod.

The value of Young's modulus for copper is 120×10^{10} dynes, and the density of copper is 8·8 grs. per c.c., hence the velocity with which sound is longitudinally transmitted through a copper rod is

$$v = \sqrt{\frac{M}{D}} = \sqrt{\frac{120 \times 10^{10}}{8 \cdot 8}} = 3693 \text{ metres per second.}$$

(*b*) In the case of gases and liquids the coefficient of elasticity is the ratio of the increase of pressure in dynes applied per unit of area to the diminution in bulk per unit volume, which this produces, both being very small. Thus, if V be the original volume of a gas and P its original pressure, and if, on increasing the pressure to $P+p$, the volume is reduced to $V-v$, its coefficient of elasticity is

$$p \div \frac{v}{V}, \quad \text{or} \quad \frac{pV}{v}.$$

By Boyle's law, if the temperature of the gas remains constant,

$$PV = (P+p)(V-v),$$

$$\text{or} \quad Pv = pV - pv.$$

Neglect pv as being the product of two quantities supposed to be very small, we get

$$P = \frac{pV}{v}.$$

Thus we can take the coefficient of elasticity of a gas to be equal to its pressure, P, in dynes per square cm. The velocity of sound in a gas is, therefore, theoretically

$$v = \sqrt{\frac{P}{D}}. \tag{ix}$$

Taking air at 0° C. and under a pressure of 76 cm. of mercury, its density, D, is ·001293 grs. per c.c., and its pressure P is $76 \times 13 \cdot 6 \times 981$ dynes per square cm., where 13·6 is the density of mercury and 981 the acceleration due to gravity.

Substituting these values in equation (ix), we deduce the velocity of sound through air at 0° C. to be 280 metres per

second. Experiment shows that the velocity, thus theoretically deduced, is more than 50 metres per second too small.

Laplace was the first to explain the discrepancy. When air expands it is cooled, when compressed it is heated. Thus, in the series of compressions and rarefactions by which sound is transmitted through it, it is alternately heated and cooled. The conductivity and radiating power of air are so small that, while the sound wave is being transmitted, there is not sufficient time for the air to regain its normal temperature. The elasticity of the air is therefore increased both because the compressions, by reason of the heat produced, have a greater power of expansion, and because the rarefactions, by reason of the cold produced, have a less power of resisting the expansion. Laplace showed that in order to take into account the above heating and cooling effects, the pressure of a gas must be multiplied by κ, the ratio of its specific heat at constant pressure to that at constant volume. The corrected equation becomes

$$v = \sqrt{\frac{\kappa P}{D}}. \tag{x}$$

For air $\kappa = 1{\cdot}41$, and the velocity of sound through it at 0° C., and at a pressure of 76 cm. of mercury, calculated from this equation, is 332·4 metres per second, which agrees with experiment.

We can deduce from this equation three important results:

(*a*) In a gas at constant temperature, an alteration of pressure does not affect the velocity of sound, since under this condition $\frac{P}{D}$ is constant by Boyle's law.

(*b*) The velocity of sound increases with the rise of temperature of the gas, since the density decreases. If v_o, v_t are the velocities of sound, and D_o, D_t are the densities of a gas at 0° and t° C. respectively,

$$v_t : v_o :: \sqrt{D_o} : \sqrt{D_t}$$
$$:: \sqrt{1 + at} : 1$$

or

$$v_t = v_o \sqrt{1 + at}, \tag{xi}$$

where a is the coefficient of expansion of the gas; in other words, the velocity varies directly as the square root of the 'absolute temperature' of the gas,

or $$v : v' :: \sqrt{T} : \sqrt{T'},$$

where T, T' are the absolute temperatures reckoned from -273° C.

For air $$a = \cdot 00366;$$

$$\therefore \quad v_t = 332\cdot 4 \sqrt{1 + \cdot 00366 t}$$
$$= 332\cdot 4 + \cdot 6t \text{ [13] metres per second.}$$

Thus for every degree rise in temperature the velocity of sound through air increases by 60 cm. per second.

(*c*) In different gases at the same temperature

$$v \propto \frac{1}{\sqrt{D}},$$

or the velocity of sound varies inversely as the square root of the density of the gas.

9. To determine the velocity of sound in air by a resonance tube.

Apparatus. Two Glass Tubes 45 cm. in length, one 4 cm. the other 5 cm. in diameter: two Tuning-forks, one of 256, the other of 320 frequency: tall Gas Jar.

Experiment. Hold one of the glass tubes vertically, with its lower end dipping under water in the gas jar. If we hold a vibrating tuning-fork over the mouth of the tube, and shorten or lengthen the enclosed column of air by raising or lowering the tube in the water, we shall find that there is one length of the air column which will reinforce the note given out by the fork most strongly. Just as one stretched wire will be thrown into vibration by another vibrating wire, only if both are tuned to unison (Note 6 (β) p. 63), so there is only one length of an

[13] $\sqrt{1 + \cdot 00366 t} = (1 + \cdot 00366 t)^{\frac{1}{2}} = 1 + \frac{1}{2} \cdot 00366 t$ approx.,

$$\therefore \quad v_t = 332\cdot 4\,(1 + \cdot 00183 t) = 332\cdot 4 + \cdot 6t.$$

air column which will reinforce a given note, and conversely there is only one note to which a given length of an air column will act as a resonator. If the air column is not of the proper length, the vibrations set up in it by the source of sound will 'interfere' with each other, and, in general, prevent the reinforcement. We can show that the length of the 'resonance column' is one quarter of the wave-length in air of the note which it reinforces thus. The forward motion of the prong of a vibrating tuning-fork, held over the mouth of the resonance column, sends a compression down the tube. This is reflected at the closed end, and reaches the mouth again just as the prong is moving back. The backward motion of the prong then causes a rarefaction to be sent down the tube, which, after reflexion at the closed end, reaches the mouth just as the prong is moving forward and starting another compression. The wave has, therefore, travelled four times the length of the resonance column between two successive compressions, i.e. while the fork has made one complete vibration. Hence the wave-length of this particular note in air is four times the length of the column.

Take two corks which fit firmly into the two glass tubes and through each pass centrally a piece of ordinary glass tubing about 4 cm. in length, and join their ends with a piece of india-rubber tubing about 30 cm. in length. Close one end of each tube with a cork, and, arranging the glass tubing so that it is flush with the inner surface of the cork, make it water-tight by a covering of wax. Support the glass tubes vertically near each other, and, after attaching a thin strip of gummed paper along their lengths, pour water in until each is half full. Holding the *C*-fork over the mouth of the wider tube, gradually lower the other one until the maximum resonance is heard, and, marking the level of the water, measure its distance below the mouth of the tube. At least six independent measures should be made, and the mean taken as the length of the resonance column. Repeat the above while holding the *E*-fork over the same tube. Now the air near the mouth is not under the same constraint as the rest of the air in the tube, so that we must apply a

correction to the lengths found above. The correction for the open end is a function of the internal diameter of the tube, and it has been proved [14] that we must add to the length of the resonance column, above measured, ·41 times the inside diameter of the tube to get with sufficient approximation what its value would be if all the air were in a similar state of constraint. If l is the corrected length corresponding to a note of frequency, n,

$$v = n\lambda = 4nl.$$

Now find the lengths of the resonance columns, using the narrower tube. Note the temperature t of the room, and enter your results in a tabular form as follows:—

Calculated velocity of sound in air at ...° C. = ... m. per sec.					
Pitch of Fork.	Internal Diameter of tube.	Length of resonance column.		Wave-length of note in air.	Velocity of sound in air at ...°C.
		Measured.	Corrected.		
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

On shortening the length of the column of air in the tube, try and get a length to reinforce the first harmonic of the tuning-fork, and compare it with the length of the resonance column as found above.

*10. To find the correction to be applied to the length of a resonance column in terms of the diameter of the tube.

Apparatus. Four Glass Tubes 45 cm. in length, and 2, 3, 4, 5 cm. in diameter respectively: the two Tuning-forks used in the last experiment.

[14] Rayleigh's *Sound*, vol. ii. p. 169.

Experiment. As in the last experiment, determine very accurately the lengths of the resonance columns in the four tubes corresponding to the fork of lower pitch. Note the temperature of the room, and calculate the true velocity of sound at this temperature. Divide it by 256, the pitch of the fork, to get the wave-length of the note in air. One quarter of this wave-length will be the true length of the resonance column. The differences between the true length and those measured above, when divided by the corresponding internal diameters of the tubes, will give that fraction of the diameters which has to be added as a correction to the measured lengths, in order to get the true length of the resonance column at the temperature of the experiment. Repeat the above, using the other fork, and enter your results in a tabular form as follows:—

Calculated velocity of sound in air at ...° C = ... m. per sec.					
Pitch of Fork.	Diameter of tube (d)	Length of resonance column.		Difference (δ)	Correction ratio $(\frac{\delta}{d})$
		Measured.	Calculated.		
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

11. To determine the velocity of sound through carbon dioxide gas by a resonance tube.

Apparatus. Two Glass Tubes, and the two Tuning-forks used in Experiment 9: Apparatus and Material to prepare Carbon dioxide gas (CO_2): a Wash Bottle containing water through which the gas must be passed in order to absorb any acid fumes.

Experiment. Fit up the two tubes as in Experiment 9, and arrange the CO_2 apparatus, so that the delivery tube from the

wash bottle is inside one of the tubes with its end about 10 cm. below the mouth. Cause a stream of CO_2 to pass into the tube, so as to keep it full of the gas, and determine as before the lengths of the resonance columns corresponding to the two forks. Enter your results in a tabular form similar to that of Experiment 9, substituting CO_2 for the word 'air.'

Compare the length of the resonance column with that obtained for air, and explain the effect of the density of a gas on the velocity of sound through it.

N.B.—This method may be employed in the case of gases (e.g. sulphur dioxide), which are heavier than air.

***12. To determine the velocity of sound through hydrogen gas by a resonance tube.**

Apparatus. A Tube nearly a metre in length and 3 cm. in diameter: a Tuning-fork of 512 frequency: Apparatus and Material to prepare Hydrogen gas: a Wash Bottle containing concentrated Sulphuric acid, through which the gas must be passed to purify and to dry it.

Experiment. Close one end of the tube with a tight-fitting cork, covering it with wax to make it perfectly gas-tight. Fit a cork to the other end to slide with slight friction in the tube, using a long stout wire for a piston-rod. Place the tube vertically mouth downwards, and push the piston up to the closed end. Arrange the hydrogen apparatus so that the delivery tube from the wash bottle passes up the tube with its end about 20 cm. above the mouth. Cause a stream of hydrogen to pass into the tube to keep it full of gas, and, holding the vibrating fork at the mouth, find the length of the resonance column by moving the piston. At least four determinations should be made, and the mean taken. Determine the velocity of sound through hydrogen gas as before, and, comparing it with your results for air and CO_2, explain the difference.

N.B.—This method may be employed in the case of gases (e.g. ammonia gas, coal gas), which are lighter than air.

***13. To prove by a resonance tube that the velocity of sound in a gas varies directly as the square root of its absolute temperature.**

Apparatus. Three glass Tubes 45 cm. in length and 3, 4, 5 cm. in diameter respectively: a Tuning-fork of 320 frequency: Thermometer: Ice.

Experiment. Connect together by a piece of india-rubber tubing, as in Experiment 9, the tubes of 3 and 4 cm. in diameter. Cut a hole out of a cork fitting the 5 cm. tube, so that the 3 cm. tube may be pushed tightly through it. Fit the cork tightly into the largest tube, and so form a jacket round the smallest. Fill the two connected tubes half full of water, supporting them vertically near each other. Hang a thermometer in the jacketed tube. Note the temperature, t, of the air inside, and, as before, find the exact length of the resonance column corresponding to the given fork, and correct it for the open end. Crush up some ice and pack the space between the two tubes with it, and place some in the water in the two connected tubes. Fill up the jacket with water. Let the apparatus remain till the thermometer has become stationary, and note the temperature, t', indicated. Determine, as before, the exact length of the resonance column corresponding to the fork, and apply the correction for the open end. Enter your results in a tabular form as follows:—

Pitch of fork = ... : Diameter of tube = ... cm.			
Temperature of the air.	Corrected length of resonance column.	Velocity of sound.	Square root of the absolute temperature.
t t'	l l'	v v'	$\sqrt{T}$ $\sqrt{T'}$

We shall find that the quotient of the velocity of sound by the square root of the corresponding absolute temperature is constant, thus proving what is required.

We can vary this experiment and determine, a, the coefficient

of expansion of air [15] by substituting the observed values of v, v', t, t' in

Fig. 3.

$$\frac{v}{\sqrt{1+at}} = \frac{v'}{\sqrt{1+at'}}$$

deduced from Equation xi.

Kundt's method of determining the velocity of sound. The principle of Kundt's method is illustrated in Fig. 3. R is a glass tube, a metre in length and 4 cm. in diameter, the ends of which are closed by the corks A and B. Through A passes a bent glass tube D, by means of which we can fill the tube R with the gas we wish to experiment upon. P is a cork sliding with slight friction in R, which we can move to any position by the glass tube passing through B. A piece of india-rubber tubing and a clip are fitted on to this glass tube. The above arrangement we shall call a **Kundt's tube.** Suppose now we take a glass tube, S, and, after attaching a piece of cardboard or thin cork C, slightly less in diameter than the tube R, to one end, pass it tightly through the cork A, so that half its length is inside and half outside the tube R, and so that the axes of the tubes are collinear. On rubbing the tube S, thus clamped in the middle, we cause it to give out its fundamental note, and the vibration of the stop C enforces the column of air in R to vibrate in unison with it. Since the velocity of sound in a solid is much greater than in a gas, the length of the column of air, PC, is too great for it to vibrate as a whole in unison with the note, and, therefore, just as the thread in Experiment 8 split up into vibrating loops, the air will split up into nodes and ventral segments. To observe them, introduce into the tube R a little fine

[15] As an estimate of the accuracy of this method, the mean of three results in a certain experiment differed 2 °/₀ from the true value.

powder forming a thin layer along its length. We may use for the purpose lycopodium powder, dry silica powder, or fine cork dust. On rubbing the tube *S*, the powder will be set in motion by the vibrating column of air, and will collect at the points of least motion, i.e. at the nodes. To get them as definite as possible move the piston *P* to the position of a node. We can thus compare the velocities of sound in air and in a solid *S*. For since both are vibrating with the same frequency, the velocities are proportional to the wave-lengths in the two media; since the wave-length in the air is twice the distance between two nodes, and in the rod twice the distance between the middle of two ventral segments, the ratio of the velocities of sound in the solid and in the air is the same as the ratio of the length of the tube *S*, clamped in the middle, to the distance between two successive nodal dust-heaps in the tube *R*[16].

***14. To prove that the velocities of sound through different gases at the same temperature vary inversely as the square roots of their densities by Kundt's method.**

Apparatus. Kundt's Tube: a Glass Tube[17] *S* about 60 cm. in length and 1 cm. in diameter, fitted with a stop *C* (Fig. 3): Apparatus and material to prepare Carbon Dioxide and Hydrogen Gases: a Wash Bottle containing concentrated Sulphuric Acid through which the gases are to be passed to purify and to dry them: Fine Powder.

Experiment. Dry the Kundt's tube by passing through it a plug of hot dry cotton wool, and, if necessary, by warming it with a Bunsen's flame. In the latter case, after rigging up the apparatus, we should let it remain till we are sure the tube has cooled to the temperature of the air. Pour a little fine powder into the tube so that it forms a thin layer along its length, and arrange it horizontally. It may rest on two *V*-shaped notches cut out of the sides of a wooden box. Fit the cork *B* and piston *P* into one end, and pass the glass tube firmly through the cork *A*, so

[16] See pp. 62 and 85.

[17] We must exercise some judgement in choosing a smooth glass tube. Specimens of glass differ so much in their value for this purpose that when we have found a suitable one it should be carefully preserved.

that it is clamped in the middle and so that the axes of the tubes are collinear. On rubbing the tube longitudinally with a cloth, wetted with methylated spirits, it gives out its fundamental note, and the dust will collect at the nodes of the vibrating column of air in definite heaps if we move the piston *P* to the position of a node [18]. Measure the length between the middle of the extreme nodes containing the most well-defined ventral segments, and divide by the number of the ventral segments to get the mean distance, *d*, between the nodes in air.

Now connect the tube *D* with the delivery tube of the wash bottle through which a stream of CO_2 is passing. Shake the tube *R* to distribute the powder evenly again, and when it is quite full of CO_2 repeat the above experiment. Suppose d_2 is the mean distance between the nodes in CO_2. Take the apparatus to pieces, expel the CO_2 and rig it up as before, connecting the tube *D* with the coal gas supply, and repeat the experiment. Connecting the tube *D* with the Hydrogen apparatus, again repeat the experiment. Observe the temperature, *t*, of the room, and enter your results in a tabular form as follows:—

$t = \ldots°$ C.

Gas.	Mean distance between two successive nodes.	Velocity of sound in the Gas (v)	Square root of the density of the gas referred to air ($\sqrt{D}$)	$v \times \sqrt{D}$
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...

With each of the gases the same pitched note was employed, hence the velocities of sound through the different gases are proportional to the respective internodal distances. Knowing the velocity through air at the temperature of the experiment, calculate and enter in the third column the velocities through the other gases. The numbers in the fifth column will be found to be constant, which proves what is required.

[18] If we watch the motion of the dust we can clearly distinguish the nature of the motion of the vibrating air. In many cases the nodes are most clearly defined in the space between *C* and *A*.

*For a more accurate result we should have to take into account the differences in their values for κ. If v_1, v_2, κ_1, κ_2, D_1, D_2 are the velocities of sound in the ratios of the specific heats and the densities of two gases,

$$\frac{v_1}{v_2} = \sqrt{\frac{\kappa_1 D_2}{\kappa_2 D_1}}. \quad \text{(Vid. Equation x.)}$$

C. VELOCITY OF SOUND THROUGH SOLIDS.

Longitudinal vibrations of rods clamped in the middle, and of columns of air in tubes open at both ends. If we clamp a rod of wood in the middle, and cause it to vibrate longitudinally by rubbing it with a resined cloth so that it gives out its fundamental note, the middle of the rod, being the point of least motion, will be a node. On both sides of the middle the particles of the

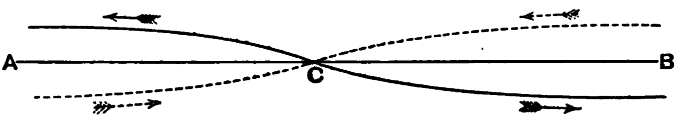


Fig. 4.

solid will vibrate about their mean position of equilibrium, in consequence of the elasticity of the solid—the particles nearer the free ends having the greater amplitudes. The free ends themselves have the greatest amplitudes and transmit, in consequence of their vibrations, compressions and rarefactions to the air which reach our ear and cause us to hear the note emitted by the rod. The ends of the rod are the middle of ventral segments, and the wave-length of the note in the solid is therefore equal to twice the length of the rod (Note 4, p. 62). Particles at equal distances to the right and left of the middle point, C, are at any given instant vibrating with equal velocities but in opposite directions, and each particle of the rod will have completed a vibration while the pulse is transmitted from the middle to the two free ends and back again, i.e. when the pulse has travelled twice the length of the rod.

If ACB (Fig. 4) is the rod clamped at the middle C, by erecting ordinates as before at each point to indicate the amplitudes in magnitude and sign of successive particles we obtain the double curve in the figure representing the motion of the particles during one complete vibration. The two branches of each curve are drawn on opposite sides of AB to represent the fact that at equal distances on either side of a node the particles have, at any given instant, velocities equal in magnitude, but opposite in direction. The same figure would apply to the case of a column of air in a tube open at both ends, e.g. an open organ pipe, giving out its fundamental. A node is formed in the middle, and the two open ends are the middle of ventral segments, the wave-length of the note in air being twice the length of the pipe.

15. To determine the velocity of sound through glass.

Apparatus. A Glass Tube a metre in length and 1 cm. in diameter: Fine Powder.

Experiment. After drying the tube sprinkle a little powder along its length, and close its ends with corks. Through one of the corks must pass a glass rod attached to another cork sliding with slight friction inside the tube to serve as a piston. Arrange the tube horizontally, and clamp it firmly in the middle. Rub it longitudinally with a cloth wetted with methylated spirits, so that it gives out its fundamental note, moving the piston to the position of a node. Dust heaps will gather at those places which are nodes, formed by the resultant effect on the enclosed air of the longitudinal vibrations of the tube and of its transversal vibrations, which, as Savart has shown, are always produced as well. It is generally hard to get the heaps to be formed at the nodes corresponding to the longitudinal vibrations of the tube alone, but, on rubbing it gently and watching the dust vibrating, we can measure the distance between middle points of the shortest ventral segments which are transitory. These are due only to the longitudinal vibrations of the tube. Take measures in different parts of the tube, and the mean as the distance, d, between two nodes. Measure the length, l, of the

tube, and note the temperature, t, of the room. Then vel. in glass : vel. in air :: l : d, therefore if v is the known velocity of sound in air at $t°$, the velocity through the glass is

$$\frac{l}{d}v \text{ metres per second.}$$

Now take out the corks from the tube and repeat the above experiment, cutting off, if necessary, from one end such a length as will make the two free ends of the enclosed column of air the middle of ventral segments, and compare your results.

16. To determine the velocity of sound through solids by Kundt's Tube.

Apparatus. Kundt's Tube: a brass, copper, and glass Tube, and a wooden Rod, each about a metre in length and 1 cm. or less in diameter, each having a stop C at one end: Fine Powder.

Experiment. The cork A of Kundt's tube will not be required. After drying the tube, sprinkle a thin layer of fine dust along its length and support it horizontally. Clamp the brass tube firmly in the middle, and arrange it so that its axis is collinear with that of the Kundt's tube, and so that it projects about 30 cm. inside the wide tube. On rubbing the tube longitudinally[19], it gives out its fundamental note, and the dust will collect at the nodes of the vibrating column of air in definite heaps if we move the piston, P, to the position of a node. Measure the length between the middle of the extreme nodes containing the most well-defined ventral segments, and divide by the number of the ventral segments to get the mean distance, d, between the nodes in air. Measure the length, l, of the brass tube and note the temperature, t, of the room. Then vel. in brass : vel. in air :: l : d, therefore, if v is the known velocity of sound in air at $t°$, the velocity through brass is

$$\frac{l}{d}v \text{ metres per second.}$$

[19] In the case of glass rub with a cloth wetted with methylated spirits; in the case of other solids a piece of chamois leather well resined is better.

Repeat the above, using successively the different rods and tubes at your disposal, and enter your results in a tabular form as follows:—

Calculated velocity of sound through air at ...° C = ... m. per sec.			
Material.	Length of rod.	Mean distance between two successive nodes.	Deduced velocity.
...	...	...	...
...	...	...	...
...	...	...	...

Compare your results with those given in the Appendix.

17. To determine the velocity of sound through solids by the monochord and a tuning-fork of known pitch.

Apparatus. Monochord: a Tuning-fork of 512 frequency: the brass, copper, and glass Tube and wooden Rod used in Experiment 16.

Experiment. Key the monochord wire to a somewhat lower pitch than that of the given fork. Clamp one of the tubes firmly in the middle. Rub it longitudinally so that it gives out its fundamental note and measure off with the moveable bridge a length, l, of the monochord wire in unison with it. Since the notes given out by the wire and the solid differ in quality, great care must be taken in adjusting the wire. If the ear is untrained a mistake of an octave is not unusual. It is better to shorten the length of the wire until the note is evidently too high, and then adjust it accurately. Now measure off a length, L, of the wire in unison with the given fork. If the frequency of the note given by the tube is n we have

$$n : 512 :: L : l,$$

$$\text{or} \quad n = \frac{L}{l} 512.$$

Measure the length of the tube. Twice the length gives us the wave-length, λ, of the note in the solid, and the velocity of sound through it is $v = n\lambda$.

Repeat the above with the other tubes and rod at your disposal, and enter your results in a tabular form as follows:—

Length of monochord wire in unison with fork of pitch ... is ... cm.					
Solid.	Length of wire in unison.	Pitch of note given out.	Velocity of sound through solid.	Density.	Young's Modulus.
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

*N.B.—Find the density of the solids used, and from Equation (viii) determine the value of Young's Modulus for each.

D. Interference of Sound.

If two systems of sound-waves of equal wave-length and amplitude, each from a different source, pass simultaneously through the air, the motion of an air particle at any instant is the resultant of the motions which each system tends to produce in it. If the compressions of one system coincide with the rarefactions of the other, i. e. if one is half a wave-length in front or behind the other, each air particle, having equal and opposite motions impressed upon it, would remain at rest and no sound would be heard. Such waves are said to *interfere* with each other. If, however, the compressions and rarefactions of one system coincide with the compressions and rarefactions of the other, the motion of each air particle would be doubled and an intensification of the sound would be the result.

Two systems of waves will therefore interfere with each other if one is any odd multiple of half a wave-length in front or behind the other, and will reinforce each other if one is any number of whole wave-lengths in front or behind the other.

If we hold a vibrating tuning-fork close to our ear, and turn it round, we shall notice there are four positions in which the

sound vanishes. At each of these four positions the difference of the distances of the ear from the two prongs is equal to an odd multiple of half the wave-length of the note given out. Therefore the waves started by each prong interfere at these points and the sound vanishes.

Again, take two glass tubes of about 3 cm. in diameter, and cut off such lengths that, when one end is closed by a cork, the length of the column of air in each is the length of the resonance column corresponding to a given fork. Now place one tube vertically on the table and arrange the other horizontally, so that the mouths of the tubes are near each other. Hold the vibrating tuning-fork symmetrically between the open ends. We shall notice no sound, if the prongs of the fork vibrate horizontally, for as one prong sends a compression down one tube the other sends a simultaneous rarefaction down the other. Thus the opposed vibratory motions issue from the mouths of the tubes, and they neutralise or interfere with each other's action on the outside air. On covering the mouth of one jar the sound is reinforced.

The beats referred to in Note 6 (*a*), p. 63, as being heard when two notes slightly out of unison are sounded together, are due to the alternate interference and reinforcement of the two systems of sound-waves emitted by them.

Suppose two notes, having the frequencies 320 and 322 respectively, are sounded together. At the end of every half-second one will have completed 160, the other 161, vibrations, at the end of every second one will have completed 320, the other 322, vibrations. Thus at the end of every half-second, the two waves will be in the same phase and will reinforce each other. At the end of every $\frac{1}{4}$ or $\frac{3}{4}$ sec. one will have made 80 and 240, the other $80\frac{1}{2}$ and $240\frac{1}{2}$ vibrations. Hence at the end of every $\frac{1}{4}$ and $\frac{3}{4}$ sec. the slower system will be half a wave behind the other, and they will interfere. Thus in one second we shall hear two beats. By a similar reasoning we can show that the number of beats per second produced by two notes slightly out of unison is equal to the difference in their frequencies. Fig. 2, p. 69, represents the simultaneous wave-motions

of two notes of frequencies 10 and 12 during one second. At *a*, *b*, they reinforce each other, and at *d* and *e* they are in opposition, thereby causing two beats per second.

18. To measure the wave-length of a given note by the method of interference.

Apparatus. (Fig. 5) [*A*, *B* are two T tubes. One arm of each is bent at right angles and the ends joined by a piece of india-rubber tubing *F*. The other arms are cut off short, and connected by tubing with two glass tubes *E* and *D*, 15 cm. long,

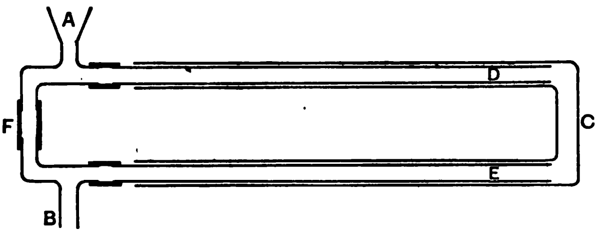


Fig. 5.

over which can slide the legs of a bent piece *C*. The tubing should be from 8 to 10 m.m. in diameter. A funnel is fitted on to the shank of *A*]: Forks of 320, 384, and 512 frequencies: Metre Rule.

Experiment. Hold one of the vibrating forks over a resonance tube in front of the funnel, and place the shank of *B* close to the ear. On gradually drawing out the tube *C* we shall find one position in which we do not hear the sound of the tuning-fork. The sound travels to the ear along two paths—one through *F*, the other through *C*. In the position at which the sound vanishes the sound-wave through *C* interferes with, i. e. is half a wave-length behind, that passing through *F*. Measure the difference of the lengths of the two paths which is half a wave-length. Repeat this three times more, and multiply the mean distance by two to get the wave-length, λ, of the sound in air. Knowing the frequency, n, of the fork, the product of these two numbers gives the velocity of sound through air, at the temperature, t, of the room, which we must also observe.

Repeat this experiment with the other forks successively, and enter your results in a tabular form as follows:—

Calculated velocity of sound through air at ...° C = ... m. per sec.		
Pitch of fork.	Wave-length.	Deduced velocity of sound in air at ...° C.
...	...	...
...	...	...
...	...	...

***19. To prove that the number of beats per second given by two notes slightly out of unison is equal to the difference of their frequencies.**

Apparatus. Monochord with two similar wires: two Tuning-forks of 256 and 320 frequencies respectively.

Experiment. If the monochord wires are out of tune, tighten the one of lower pitch so as to bring it gradually into unison with the other. We shall notice that the number of beats produced when both are vibrating decrease until they vanish when both are exactly in unison. On still increasing the tension we raise its pitch above the other one, and the number of beats again increase. Tune both wires to give the same note slightly lower than one of the tuning-forks. Fix the moveable bridge under one of the wires at such a length, L, as will give a note exactly in unison[20] with the fork. Fix the other moveable bridge under the other wire at such a length, l, as when both wires are set into vibration beats may be heard slow enough to be counted. With your watch count the number of beats produced in ten or fifteen seconds, and calculate the number during one second. Care must be taken not to include the first beat when you begin counting. If n is the frequency of the fork, the pitch of the shorter wire is

$$\frac{L}{l}n,$$

[20] This should be done very carefully, using both methods of Note 6, to ensure perfect accuracy.

that of the longer is n. The difference of the pitches of the two wires will, if the observations have been carefully made, be found to be the same as the number of beats produced per second.

Repeat this on making the length of the second slightly longer than that of the first wire, and again by using the other tuning-fork.

20. Experiments with singing flames.

Apparatus. Four thin glass Tubes 2 cm. in diameter, two of 40, two of 80 cm. in length: Paper Cylinders of the same lengths as the tubes, to slide tightly over them: two Gas Jets, which may be made by drawing out pieces of glass-tubing ·75 cm. in diameter, so that the nozzles are the same size and give flames about 6 cm. in length: Plane Mirror.

Experiments. (*a*) Connect one jet with the gas supply, and, supporting it vertically, light the issuing gas. Over the jet clamp vertically one of the shorter glass tubes, so that the jet passes up about 2 or 3 cm. inside. Alter the position and size of the flame till the tube gives out a pure musical note—the wave-length of this note being approximately equal to twice the length of the tube (p. 86). Turn the mirror quickly to and fro in front of the jet, and notice the appearance of the flame as reflected in it. It will appear to consist of tongues of flame showing that while the tube is sounding the flame is alternately extinguished and relit. The vibrations which the tube reinforces are due to these alternations, which are too quick to be noticed by the unaided eye.

(*b*) Now set up the other short tube clamped similarly over the second jet, and arrange the two so that the notes given out by the two tubes are in complete unison. On altering the length slightly of one tube by sliding its paper cylinder over it, we notice loud and almost unbearable beats due to the two sounds, the beats being slower the more nearly they are in unison.

(*c*) On doubling the length of the tube by placing the cylinder vertically over its upper end, the note given out will

be approximately the octave lower of the original note, since the frequency of a note varies inversely as the wave-length in air at a constant temperature. Repeat these experiments with the two longer tubes, and show that the note given out by a longer is the octave lower than that given out by the shorter tube.

(*d*) The wave-length given out by a tube closed at one end is four times its length (Experiment 9), that given out by a tube open at both ends is twice its length. Prove this by observing that the note given out by the shorter tube, when its upper end is closed by a piece of cardboard, is the same as that of the longer tube open at both ends.

Appendix B.

(1) *Velocity of Sound in metres per second.*

(α) *Solids:—*

Brass	3479
Copper	3825
Flint Glass	3996
Glass	4995
Iron	5000
Beech	3412
Oak	3381
Pine	4650

(β) *Gases at 0° C:—*

Air	332·4
Coal Gas	490
Hydrogen	1280
Carbon Dioxide	262
Ammonia	415
Oxygen	317

(2) *Densities of Gases referred to air at the same temperature and pressure.*

Air	1·000
Oxygen	1·106
Hydrogen	·069
Carbon Dioxide	1·530
Coal Gas	·340 to ·650
Sulphur Dioxide	2·211
Ammonia	·597

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